PB-239 710

NICKEL-ZINC BATTERIES FOR HYBRID VEHICLE OPERATION

Martin J. Sulkes

Army Electronics Technology and Devices Laboratory

Prepared for:

Environmental Protection Agency

December 1972

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA-460/3-74-025	2.
3. PB 239 710	
4. TITLE AND SUBTITLE Nickel-Zinc Batteries for Hybrid Vehicle Operation	5. REPORT DATE December 1972
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Martin J. Sulkes	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Electronics Technology and Devices Laboratory U.S. Army Electronics Command Fort Monmouth, New Jersey	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Air and Waste Management Office of Mobile Source Air Pollution Control Ann Arbor, Michigan 48105	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Un-numbered interagency agreement

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 57
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EPA-460/3-74-025

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Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Mobile Source Air Pollution Control
Alternative Automotive Power Systems Development Division
Ann Arbor, Michigan 48105

December 1972

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Nickel-zinc batteries have been evaluated against the requirements of a hybrid electric vehicle regime. This regime consists of many short duration pulses at high rates of discharge with rapid recharge. High rate designed conventional Ni-Zn batteries of a nominal 24 Ah capacity yielded up to 26,000 Ah total output (equivalent to 150,000 cycles) before failure; this compares to a desired output of 73,000 Ah or 400,000 cycles. The principal failure mechanisms were shorting and loss of voltage due to high carbonate concentrations caused by degradation of the cellulosic separator. Zinc shape change (10-20%) was surprisingly low in view of the large number of cycles. The nickel electrodes were essentially unaffected by the cycling. Rapid and complete recharge was accomplished with a modified constant potential of 1.83V/cell. The use of this voltage resulted in low heat generation, approximately 7-8 Btu/cell/h and a low percentage of overcharge. Overall energy efficiency on the hybrid vehicle test regime is as high as 89%. Two types of inorganic separator material were evaluated, and were found to be unsuitable. A full size battery, to power a hybrid electric vehicle, would consist of 120 cells. The battery would weigh 350-400 lbs; the charging voltage would be 220V. The average discharge voltage would be 207V at a 10kW load and 165V at a 55kW load.

Foreword

This report presents the work performed by the US Army Electronics Technology and Devices Laboratory (ECOM) in evaluating advanced nickel-zinc battery concepts for a heat engine/battery hybrid for family car propulsion. In this application the battery stores part of the energy provided by the heat engine and supplies it when acceleration power is needed. The engine thus operates essentially at steady state, and thereby reduces exhaust emissions. This work, conducted for the Environmental Protection Agency under an interagency agreement covered by EPA Obligation Code 690403, extended from May 1971 to November 1972.

The assistance of Dr. J. Salihi of the Advanced Automotive Power Systems Development Division, Office of Air and Water Programs, Environmental Protection Agency, is gratefully acknowledged.

TABLE OF CONTENTS

PAGE NO.

INTRODUCTION.....1

DISCUSSION.....1

Nickel Electrode.....3
Zinc Electrode.....3
Separator.....4

EXPERIMENTAL RESULTS.....4

Storage Life of Standard Nickel Zinc Cells.....4
Voltage-Current Characteristics of Standard and Advanced Eagle-Picher Ni-Zn Batteries.....5
Cycle Life Test Regime.....7
Cycling Equipment.....8
Cycle Life Data for Standard Eagle-Picher Ni-Zn Batteries.....8
Cycle Life Data for Advanced, High Rate Design, Eagle-Picher Ni-Zn Batteries.....10
Cycle Life Data for Advanced, High Rate Design, Energy Research Corp., 4 Ah, Ni-Zn Batteries.....14
Cycle Life Data for Advanced, High Rate Design, Energy Research Corp., 20 Ah, Sealed Ni-Zn Batteries.....16
Battery Heat Generation and Removal.....17
Gas Generation.....19
Battery Failure Analysis on Standard and Advanced Eagle-Picher Ni-Zn Batteries.....19
Battery Failure Analysis on Cells with Non-Sintered Positive Electrodes.....21
Cells with Inorganic Separators.....22
Recommended Battery Design.....23

CONCLUSIONS.....24

REFERENCES.....25

TABLES

TABLE NO.		PAGE NO.
I	Construction Parameters for Eagle-Picher Standard and Advanced Ni-Zn Batteries	6
II	Capacity Maintenance of Advanced, Eagle-Picher, High Rate Ni-Zn Battery #1H	11
III	Capacity Maintenance of Advanced, Eagle-Picher, High Rate Ni-Zn Battery #2H	13
IV	Battery Design Parameters for Energy Research Corp., High Rate 4 Ah Ni-Zn Cells	14
V	Performance of 5 Cell, Energy Research Corp., 4 Ah Ni-Zn Battery	16
VI	Battery Design Parameters for Energy Research Corp., 20 Ah Sealed Ni-Zn Batteries	17
VII	Calculation of Battery Heat Generation	18
VIII	Failure Analysis of Eagle-Picher Ni-Zn Batteries	20
IX	Capacity Analysis of Nickel and Zinc Electrodes after 16,500 Ah	21

FIGURES

FIGURE NO.		
1	Cycle Life Versus Depth of Discharge for Various Battery Systems	26
2	Total Energy Output as a Function of Depth of Discharge	27
3	Charge Current Versus Charge Voltage as a Function of State-of-Charge for Standard Eagle-Picher Ni-Zn Battery	28
4	Charge Current Versus Charge Voltage as a Function of State-of-Charge for Advanced, High Rate, Eagle-Picher Battery,	29

FIGURES (CONT)

PAGE NO.

FIGURE NO.

5 Voltage-Current Characteristics of High Rate Ni-Zn Batteries as a Function of State-of-Charge 30

6 Discharge Voltage for 350 Ampere Load.....31

7 Cycling Histogram for Standard, Eagle-Picher Ni-Zn Battery BB-674( )/U (#1).....32

8 Cycling Histogram for Standard, Eagle-Picher Ni-Zn Battery BB-674( )/U (#2).....33

9 Deep Discharge Curves for Standard, Eagle-Picher Ni-Zn Battery #1 After Pulse Cycling.....34

10 Effect of Cycling on Deep Discharge Capacity and Voltage of Standard Eagle-Picher Ni-Zn Battery #2.....35

11 Cycling Histogram for Advanced, High Rate, Eagle-Picher Battery #1H.....36

12 Power Test Performance as a Function of Life for Advanced, High Rate, Eagle-Picher Battery #1H.....37

13 Cycling Histogram for Advanced, High Rate, Eagle-Picher Battery #2H.....38

14 Power Test Performance for Advanced, High Rate, Eagle-Picher Battery #2H.....39

15 Power Test Performance of Energy Research Corporation, 5 Cell, 4 Ah, Ni-Zn Battery.....40

16 Separator Removed from Standard Eagle-Picher Battery #1 After 13,000 Ah.....41

17 Zinc Electrode Removed from Standard Eagle-Picher Battery #1 After 13,000 Ah.....42

18 Zinc Electrode Removed from Advanced, High Rate Eagle-Picher Battery #2H After 26,400 Ah.....43

19 Nickel Electrode Removed from Standard Eagle-Picher Battery #1 After 13,000 Ah.....44

FIGURES (CONT)

FIGURE NO.		PAGE NO.
20	Nickel Electrode Removed from Advanced, High Rate, Eagle-Picher Battery #2H After 26,400 Ah	45
21	Capacity Maintenance of Astropower Sealed 40 Ah Silver-Zinc Cells	46
22	Charge-Discharge Characteristics of a Ni-Zn Cell with Astropower Separator and Zinc Electrode	47
23	Capacity Maintenance of Ni-Zn Cells with Astropower Separator and Zinc Electrodes	48

INTRODUCTION

The goal of this study was to evaluate and improve the characteristics of nickel-zinc secondary batteries for use in hybrid electric vehicles. The hybrid electric vehicle has a propulsion system consisting of a heat engine and a battery. The heat engine supplies steady state power, while the battery provides the transient power demands. The primary purpose, for hybrid propulsion, is to reduce exhaust emissions from street vehicles.

The nickel-zinc secondary battery possesses a unique combination of properties which makes it a strong candidate for use in hybrid electric vehicle propulsion systems. These properties include high energy density (25 Wh/lb), a flat discharge, and the ability to charge and discharge at high rates (greater than 100 Wh/lb) and low temperatures. Another feature of interest for vehicle propulsion use is the fact that electrode materials are plentiful and of reasonable cost. The overall cost of a nickel-zinc battery can be projected with reasonable confidence to approximately $0.15/Wh or $2-3/lb in large quantities. However, several possible problem areas do exist regarding the use of nickel-zinc cells, as presently designed, for this application; these are short cycle life and fairly high maintenance.

DISCUSSION

A nickel-zinc battery for hybrid vehicle applications should be capable of meeting the following levels required by EPA:

Voltage: 200 - 220 V open circuit
150 V minimum closed circuit voltage

Maximum Power: Discharge - 55 kW for 50 seconds
Recharge - 30 kW for 50 seconds

Maximum Capacity Required (At Maximum Power): 5.0 Ah

Weight: 350 pounds, maximum

Cost: $550 maximum

Maintenance: Minimum maintenance during life is desired

Life: Should be capable of yielding above power after 5 years and 400,000 cycles. The detailed breakdown of the total 400,000 cycles is shown on the following page.

Number Cycles	Discharge Rate (kW)	Amps*	Pulse Time (Sec)	Ah Out	Total Ah Out
1,000	50	310	27.2	2.34	2,340
5,000	55	343	8.6	0.82	4,100
5,000	55	333	5.2	0.48	2,400
389,000	10	55	10.8	0.164	64,100

*The currents shown are based on the average expected discharge voltage.

The number, length, and amplitude of the various cycles given above are based on the power requirements for the Federal Driving Cycle for a 4,000 lb family car (1). The Federal Driving Cycle consists of various stops, starts, accelerations, decelerations, and steady state periods representing actual driving practice in an urban environment. During the course of this study, EPA modified the hybrid battery power requirements (2). However, since the aim of this program was mainly to obtain information, rather than hardware, no changes were made in the specified test cycles.

In order to properly size the battery for the required life, projections were required of life versus depth of discharge. This information was not available for the nickel-zinc system, at the hybrid electric vehicle cycling regime. Therefore, first estimates were based on whatever information was available for nickel-zinc batteries, plus any information for nickel-cadmium and silver-zinc batteries. Figure 1 presents the cycle estimates for various battery systems as a function of the depth of discharge. The curves presented represent averaging and interpolation of the data available in Crane Naval Ammunition Depot Test Reports (3) and other reports. Figure 2 presents the same data, converted to yield total Ah/Ah of rated capacity versus depth of discharge. Conversion of data from Figure 2 indicates that a nickel-cadmium battery of about 12-15 Ah capacity would be capable of yielding the 73,000 total Ah required for the hybrid vehicle regime. A silver-cadmium battery would have to be rated at 73 Ah, while a silver-zinc battery might have to be 140 Ah size. The silver systems, however, would not function for the 5 year requirement because of silver attack on the separator.

Projections of nickel-zinc cycle life, based on data obtained for 60% depth of discharge, indicate that a 30 Ah nickel-zinc cell would meet approximately 1/2 the EPA hybrid vehicle battery requirement of 400,000 cycles or 73,000 Ah previously described. This expected level of performance would equal the EPA requirement for Pb-acid batteries of 36,500 Ah total. An improved nickel-zinc battery would be needed to meet full requirements. However, because only one data point for nickel-zinc was available at the start of the program, considerable testing was required to determine the actual life.

Three main areas of concern in the design of nickel-zinc cells for the hybrid vehicle applications were the nickel electrode, zinc electrode, and separator.

Nickel-Electrode

The presently available sintered nickel electrode structures are more than capable of achieving the desired life and rate capability. In fact, if the normal ratio of nickel to zinc capacity (1/3) was used, the nickel electrode would be considerably overdesigned. As the data for nickel cadmium cells in Figure 2 indicates, it would be possible to meet the requirements with a nickel capacity of less than 15 Ah. Because of plate size considerations, with sintered electrodes, it was not feasible to reduce the nickel capacity that low. However, a nickel capacity of 20-25 Ah was both feasible and desirable. The required nickel capacity was achieved through the use of lightly loaded, thin nickel electrodes. This resulted in improved high rate performance, potentially lower cost and weight. Further small improvements in performance could have been achieved through modifications of plaque preparation parameters. This might have included such changes as increasing sintering temperature and time to achieve stronger more conductive plaques. However, time did not permit investigation of these variables.

The use of a non-sintered nickel-electrode structure permits tailoring the plate thickness, loading, and conductive additives to optimize for this application. Energy Research Corp. (4) has developed a non-sintered nickel electrode that can be made thinner than plaque types and has a lower weight per Ah. Cells using these non-sintered electrodes will be more fully described later in this report.

Zinc Electrode

Teflonated, oversized, and contoured zinc electrode structures have yielded high cycle life in both silver-zinc (5,6) and nickel-zinc cells (7) cycling at 62% and 100% depth of discharge. Up to 600 cycles, which equals a total of 360 Ah/Ah of rated capacity, has been obtained in silver-zinc cells at a 62% depth of discharge regime. In most cases, failure was due to separator deterioration. The zinc electrode was still capable of yielding more than 62% of rated capacity. In silver-zinc cells, the theoretical capacity of the zinc electrode was 3 times the rated capacity. Similar zinc electrode theoretical capacities have been used in nickel-zinc cells. Studies have indicated that increasing the amount of negative electrode material will increase cycle life considerably. With a lower capacity positive, it was possible to use the space and weight available to further increase the zinc capacity.

Two minor areas still needing further investigation to optimize the zinc electrode are the percent amalgamation and the grid material. Tests

at ECOM have indicated that maximum cycle life and zinc stability are obtained with minimum mercury contents, 0-0.5%, rather than 2% mercury which is used for minimum gassing. However, for sealed operation 2% mercury may be required.

Silver-zinc and nickel-zinc cells are normally fabricated with silver Exmet type grids since they have the highest conductivity and do not promote self discharge of zinc. However, the cost of a silver grid is high; in fact, it may represent a major portion of the cost of a finished zinc electrode. Tests of cells with iron grids have been satisfactory to date from the standpoint of performance. However, hydrogen generation is higher. Nevertheless, the rate of self discharge of the negative would still be below that of the positive. Additional experimentation in this area will be required to obtain the lowest cost zinc electrode consistent with good cycle life and minimum hydrogen generation.

Separator

The weakest element in the nickel-zinc system is the separator. Organic materials, such as cellophane, can be oxidized and weakened by the attack of nascent oxygen generated during overcharge. This then results in premature shorting, as zinc grows through the cracks formed. However, over 200 deep cycles, equal to a total of 150 Ah/Ah of rated capacity, have been obtained in cells with cellophane or sausage casing separators if certain procedures are followed. These include coating the exposed edges of the separator with vinyl (8) and the use of zinc electrodes that are designed for minimum shape change.

Radiation grafted polyethylene has greater physical stability and resistance to shorting than cellulosic separators. However, it has lower conductivity which reduces power density and causes more rapid shape change on the zinc electrode.

Non-oxidizable inorganic separators offer the best hope for increasing the cycle life of the nickel-zinc system. It is estimated that cycle life could be at least doubled, if separator failure is eliminated, before the limitations of the zinc electrode begin to be felt. Inorganic separator materials investigated include the materials originally developed by Douglas-Astropower and now available through NASA-Lewis, and the layer hydroxide inorganic separator structures developed by Energy Research Corp.

EXPERIMENTAL RESULTS

Storage Life of Standard Nickel-Zinc Cells

The capacity retention of the nickel-zinc system on stand is approximately the same as that for the nickel-cadmium system. For example; data

reported by Broglio (9) indicates that capacity retention of the 35 Ah Nickel-Zinc BB-674( )/U* Battery is 75% after 28 days at 25°C and approximately 50% after 7 days at 60°C. The gassing rate of this battery on stand at 25°C is approximately 5 cm^3/Hr/cell. If this gas is all hydrogen, as would be expected, then it would correspond to a capacity loss of .25 Ah/day or 7 Ah for 28 days. Seven Ah represent a capacity loss of 20% over this period of time, compared with a 25% capacity loss by the cell, indicating that the nickel electrode controls capacity loss on stand.

The effect of prolonged wet uncontrolled storage on the nickel-zinc system was determined on a limited number of sample cells approximately 2-2 1/2 years old. Though several types from different manufacturers were available, only those from General Telephone and Electronics (GT&E) were available in adequate quantity and have sufficient reliability for a meaningful evaluation. The construction of these cells, which were activated April 1969, was given by Blickwedel (10). Seven-Ah cells containing two different types of negative electrodes were charged and discharged for up to 4 cycles. The capacities obtained were then compared with the initial performance of comparable cells. After 2 years of storage the cells with Teflonated zinc electrodes (25.7 Ah theoretical zinc capacity) yielded capacities equal to or greater than were obtained initially, except for the first cycle after storage. The capacity on this cycle was only 50% of that obtained before storage. Cells with sprayed zinc electrodes (13 Ah theoretical capacity) gave only 60% of their initial capacity after 2 years of storage after 3 cycles. It is thought that poor initial capacity after discharged stand is due to a partial passivation of the zinc. Therefore, with a large excess of zinc oxide such as was used in the Teflonated zinc electrode cells, and in cells designed for hybrid operation, no problems should be encountered if the hybrid batteries are stored discharged for several years prior to use.

Voltage-Current Characteristics of Standard & Advanced Eagle-Picher Ni-Zn Batteries

Charge current versus potential as a function of state of charge, and discharge voltage for high rate discharges were determined for 3 types of 6.4V, nickel-zinc batteries. They were the BB-674( )/U and two high rate designs in the same size case manufactured by Eagle-Picher Industries (EPI). The construction parameters of these three battery designs are given in Table I.

---

* Military Standard nomenclature, use of "( )" in nomenclature indicates battery has not been formally procured.

Table I. Construction Parameters for Eagle-Picher Standard and Advanced Ni-Zn Batteries

	BB-674( )/U	High Rate #1H & #2H	High Rate #3H
Rated Capacity (Ah)	35	24	24
Initial Capacity (Ah)	38	24.5	24
Weight	8 lb 12 oz	8 lb 15 oz	9 lb 6 oz
Positive Electrode number	10 +2	16	16
size (10)	2.81 x 5 x .037	2.81 x 5 x .020	2.81 x 5 x .020
(inches) (2)	2.81 x 5 x .025		
Negative Electrode number	11	17	17
size (in)	2.81 x 5 x .035	2.81 x 5 x .021	2.81 x 5 x .024
Theoretical Capacity (Ah)	150	125	155
Negative Tabs	2, .016" Dia Ag Wire	2, .01" x 1/8" Ag Foil	2, .01 x 1/8" Ag Foil
Separator (going from positive to negative electrode)	Pellon bag/2TFSC*/ Pellon bag	2TFSC/Pellon bag	2TFSC
Active Area (in^2)	300	436	436

*FSC (Fibrous Sausage Casing)

Voltage versus current was also determined for a battery consisting of 4 each 35 Ah cells manufactured by the General Electric Co. for another use. However, these cells had an active area of only 165 in^2 and therefore were not able to meet the requirements for the hybrid application.

The voltage-current characteristics of the batteries were determined using a test method designed to simulate actual use conditions. The battery was first run on the life cycle regime for several hours, as described later; then following a series of discharge pulses, the charge voltage was varied and the average charge current measured. The battery was then subjected to a series of discharge pulses, 10.8 seconds in length, at various currents to determine discharge voltages with charge periods of 50.2 seconds interspersed to return the battery to full charge. The battery was then discharged at 55 A until 25% of rated capacity had been removed (8.75 Ah for the BB-674( )/U and 6 Ah for battery #2H). The charge and discharge regimes described above were repeated and current-voltage measurements were taken.

The amount of charge and discharge capacity entering and being withdrawn from the battery was measured on 2, HBS* digital ampere-hour meters. Using this exact knowledge of the battery state-of-charge, additional capacity was withdrawn at 55 A to reduce the battery's state-of-charge to 50% of rated. The current-voltage characteristics for both charge and discharge were again determined. Figures 3 and 4 show the charging characteristics of the BB-674( )/U and the high rate battery (2 H), respectively, as a function of state-of-charge, while Figure 5 compares their discharge voltage-current characteristics. The 50% state-of-charge could not be maintained because of the high charge acceptance of the batteries. Therefore, the data for 50% state-of-charge represents a state-of-charge range from 50% to 65%. Depending on the minimum acceptable voltage, power densities exceeding 300 W/lb can be obtained with the high rate designed Ni-Zn battery and up to 200 W/lb with the BB-674( )/U. Both battery types were run at a 350A load for 50 seconds to simulate the 55kW power test. The voltages obtained are shown in Figure 6. The improvement in discharge voltage with the high rate design was due to the fact that it has 45% more electrode area, increased tabbing on both positive and negative electrodes, heavier terminals, and intercell connectors.

Cycle Life Test Regime

The most important consideration in choosing a Ni-Zn battery is how it will perform over a cycling regime representative of actual vehicle use conditions. Obviously a cycling regime carried out over a period of 5 years is not practical, therefore, a simulated regime had to be devised. The following regime was chosen as a reasonable compromise between the conflicting demands of realism and testing time.

1. 1 pulse at 10 kW rate (55A based on 210V battery discharging at an average 182V) for 10.8 seconds every minute for 29 out of every 30 minutes.

2. 1 pulse at 55 kW rate (350A based on 210V battery discharging at an average 157V) for 10.8 seconds every 30 minutes.

The following energy would be supplied by the battery each day:

$$55A \times \frac{10.8}{3600} \text{ seconds} \times 58 \frac{\text{pulses}}{\text{hour}} \times 24 \text{ hours} = 228 \text{ Ah}$$

$$350A \times \frac{10.8}{3600} \text{ seconds} \times 2 \frac{\text{pulses}}{\text{hour}} \times 24 \text{ hours} = 50 \text{ Ah}$$

Total Energy per Day = 278 Ah

To yield a total 73,000 Ah would require 262 days.

---

* HBS Equipment Division, Los Angeles, California.

The load, therefore, would be made up of 360,400 10 kW pulses + 12,600 55 kW pulses. Recharge rates were high (120A maximum) in order to fully recharge the cells in the short time available. Maximum charge acceptance is important in hybrid service in view of a factor such as regenerative braking. In addition, periodic test discharges of 55 kW for 50 seconds (power test) were to be performed approximately once a week to determine the ability of the battery to meet the power requirements. Deep discharges at the C/2 rate were to be performed after every 3rd power test.

During the course of cycling, several variations to the above cycling regime were made for a variety of valid reasons; for example, the discharge loads were run at fixed currents rather than fixed power, for easier comparison of different cell designs. Thus, depending on the output voltage, the load could exceed or be less than the specified power levels. In most cases, except at the end of life, the batteries generally delivered more power then the specified levels. Deep cycles were usually run more frequently than scheduled in order to obtain additional data and to recondition the batteries.

Cycling Equipment

The cycling equipment consisted of timing clocks, a Harrison Model 6456B power supply, and a water-cooled Metrodyne (800 Amp) load module. Measurement of the total charge input to the battery in Ah was obtained from an HBS digital ampere-hour meter. Protection against battery failure was provided by a voltage sensing Beede meter relay. Any sudden drop in discharge voltage, such as would occur if a short occurred, disconnected the charging and discharging units. The 55 kW, 50 second power test was run on the same equipment with minimum modification. Charge current and battery voltage were recorded on a Hewlett-Packard Model 7100B 2 pen recorder.

Cycle Life Data For Standard Eagle-Picher Ni-Zn Batteries

The initial batteries cycled were BB-674( )/U's. They were available at the start of the program and were used to determine the general response of the Ni-Zn system to the hybrid vehicle cycling regime, even though it was recognized that they delivered insufficient voltage to pass the 55 kW power test.

Figures 7 and 8 are histograms of the cycling run on 2, 6.4 V, 35 Ah BB-674( )/U Batteries. The histograms include information on the discharge voltages at 55 and 350 A, the battery external temperatures, and the percent of the charge current going into overcharge. The overcharge percentage is determined as follows:

$$\% \text{ Overcharge} = \frac{Ah_o - Ah_i}{Ah_i} \times 100$$

Ah_i = Total Ampere-hour input to battery during time (T).
Ah_o = Total Ampere-hour output to load during time (T).
T = Time period for measurement (usually 24 hours or more)

Battery #1, shown in Figure 7, was filled with electrolyte in April 1971 and run for a total of 16,650 Ah (equal to approximately 90,000 cycles) before cycling was terminated January 1972 because of low voltage during the 350 A discharge and the development of slow short circuiting. During the course of the cycling shown in Figure 7, there was a gradual decrease in discharge voltage especially at the 350 A rate. Periodic deep discharges increased the subsequent pulse voltage levels, but the effect was not permanent. This battery was charged at 2 voltage levels, 7.4 and 7.6 volts, or 1.85 and 1.90 V/cell, respectively. Since the lower potential effectively maintained charge and minimized overcharge, 7.4 V was chosen as the preferred constant potential limit. The typical percentage of overcharge at 7.4V was 2-3% except when the zinc electrode was not fully charged, then the overcharge was 7-10%. This 7-10% overcharge was measured at the beginning of charge, when uncharged zinc oxide was being charged, and at 6,500 Ah after a reversal, when the zinc had been completely discharged. Excess rates of overcharge were also measured after 14,000 Ah of cycling when shorting developed.

Battery temperature generally showed a slow increase with time and can be related to a corresponding drop in battery discharge voltage. In general, the temperatures measured were not excessive except at the end of cycling, when shorting occurred and the excess charge was 13% of the output current.

Battery #2, shown in Figure 8, was filled with electrolyte in January 1972 and run for a total of 13,000 Ah before cycling was terminated in March 1972 due to short circuiting after a deep cycle. During the cycling of this battery, one cell developed a short at 5,000 Ah and was by-passed, with cycling continued on the remaining 3 cells. In order to simplify the data in Figure 8, the voltage values obtained have been reported on the basis of a 4-cell monoblock. The same general pattern of decreasing voltage with cycling was noted with battery #2 as for battery #1. However, the voltage levels achieved for the 350 A discharge were up to 25% higher for battery #2, compared to battery #1. This may be due to the fact that battery #1 had been deep cycled 7 times at varying environments and had stood for 6 months prior to the start of cycling. Battery #2, on the other hand, was given only one deep cycle and then started immediately on cycling.

The effect of pulse cycling, on deep cycle capacity, is shown in Figures 9 and 10 for batteries #1 and #2, respectively. The voltage degradation for battery #1 is considerably more severe than the corresponding capacity loss; for example, at 13,000 Ah output, battery #1 yielded 17 Ah to 5.0 V while battery #2 yielded 17.3 Ah. The corresponding average voltages for the 14 A discharges were 5.55 V for battery #1 and 6.35 V for battery #2. The discharge curves in Figure 9 for battery #1 show a considerable slope, indicative of an increase in internal resistance with decreasing state of charge. Reference electrode measurements made at 6,500 Ah

indicated that most of the voltage loss was due to the zinc electrode. By discharging to reversal, to convert all the active zinc to zinc-oxide, the curve shown in Figure 9 for 6,540 Ah was obtained. This curve is flat and remains at a high level throughout the discharge and is typical of a nickel limited discharge. The other curves on Figure 9, however, are more indicative of zinc limited discharges. Figure 10 shows that battery #2 did not suffer excessive voltage losses due to cycling. Failure analysis was performed on batteries #1 and #2 to determine the cause of failure and the reasons for the differences between them.

Cycle Life Data for Advanced, High Rate Design, Eagle-Picher Ni-Zn Batteries

Three high rate designed 6.4V monoblocks were received from Eagle-Picher Industries; two of them were started on cycling during March 1972. The specific design features of these batteries were presented in Table I. The difference between them, was that Battery #1H was built with pellon bags on the negative electrodes, while Battery #3H had no pellon bags, but an increased weight of zinc oxide. Figure 11 is a histogram of the cycling run on Battery #1H. The histogram includes information on the discharge voltages at 55 and 350 A, the battery external temperatures and the percent of the charge current going into overcharge. Battery #3H was run under the same conditions as #1H but only lasted for 3700 Ah before a power test failure indicated some difficulty. A deep cycle was run and upon recharge it was determined that one cell of Battery #3H had shorted. It was felt that the removal of all the pellon interseparator made this design more liable to shorting. No gain in voltage was achieved by eliminating the negative pellon bag. Therefore, cycling was terminated on Battery #3H at 3,700 Ah, but continued on Battery #1H to failure. As Figure 11 shows, Battery #1H maintained good capacity and voltage levels until shorting developed. During the course of cycling, this high rate battery operated at a high voltage level for almost 8,000 Ah when lack of electrolyte became apparent. This extended period without water or electrolyte additions was made possible by the low average overcharge required by this battery. This also resulted in a lower operating temperature. After 12,000 Ah of operation, slow shorting apparently developed in one or two cells. The battery was deep cycled, recharged, and then subjected to reversal in an attempt to break the shorts. This attempt was unsuccessful, as shown by the complete failure within 400 Ah after cycling was reinitiated. Except for the shorting this battery appeared capable of considerably more cycling. Table II gives the deep cycle capacity and average discharge voltage.

Table II. Capacity Maintenance of Advanced, Eagle-Picher, High Rate Ni-Zn Battery #1H

Total Ah Delivered	Capacity (Ah)*	Average Discharge Voltage (V)
Initial	24.5	--
@ 3,700 Ah	23.1	6.4
@ 9,074 Ah	14.0	6.2
@ 9,100 Ah after addition of KOH	21.0	6.3
@ 12,412 Ah	21.0	6.3
@ 12,433 Ah	15.4 Ah to 5.0 V** +50 Ah to 1.0 V***	6.5

*Batteries discharged at 14 A to 5.0 V; charged at 4 A for 6.5 hrs.
** Some loss of capacity due to shorting on stand
***Battery reverse discharged at 3.0 A.

Figure 12 shows the voltage output during the power test of Battery #1H as a function of the ampere-hour output of the battery. After 9,800 Ah, when electrolyte had been added to the battery, it was still unable to supply 50 seconds continuously at 350 A. However, it might be possible to supply two 25 second periods at this current. At 12,300 Ah, the loss of voltage on the power test reflects the development of shorting in several cells.

High rate Battery #2H, which was identical in construction to #1H, was started on cycling after the failure of #1H. The charge voltage for Battery #2H was reduced to 7.2 from the 7.4 V used to charge Battery #1H in an attempt to reduce overcharge and lower the average battery temperature. It was hoped that this step would preserve separator integrity, prevent shorting, and extend cycle life. A histogram of the cycling behavior of Battery #2H is shown in Figure 13. When Figures 11 and 13 are compared, it can be seen that the reduction in charge voltage did have several effects, first, the temperature was approximately 10°F lower; second, the amount of overcharge was lowered; third, the discharge voltages were somewhat lower; and fourth, the number of cycles to the first short was increased by 75%. The lower voltage at the 55 A discharge is caused primarily by the lower starting voltage for the discharge, probably due to a reduced amount of more active nickel-oxides. A reduction in the charging voltage of 0.2 V (0.05 V/cell) caused a reduction of 0.15 V in the battery discharge voltage

at 55 A, while the later increase in charging voltage of 0.1 V to 7.3 V resulted in an 0.08 V increase.

The lowest possible charge voltage appears to give the greatest efficiency. For the 350 A load, the discharge voltage was reduced 0.2 V by the reduction of 0.2 V in the charging voltage, however, it is believed that this is primarily due to the fact that the battery is cooler and hence has a higher resistance. On cycling, after Batteries #1H and #2H had been on stand and were at approximately the same temperature, the voltage difference caused by the lower charge voltage was considerably smaller. During the course of cycling Battery #2H, occasional low voltages and unusual voltage dips were recorded during power tests, and also starting at about 5,200 Ah, on some of the 350 A pulses. These low pulse voltages occurred somewhat randomly and appeared to indicate a possible reduction in battery state-of-charge. Accordingly, the charge potential was raised from 7.2 to 7.3 V at 6,500 Ah. This increased the discharge voltage, as previously mentioned, but did not completely eliminate low voltage pulses.

Figure 14 shows typical power test output voltages for Battery #2H after 8,530 Ah of operation. The variation in performance for the 350 A discharge is clearly seen from the difference between Curves A and B in Figure 14. The only difference in conditions between the curves is that the higher one, Curve B, was run 2 hours after the other. The loss in voltage shown in Curve A was caused by one cell going to reversal. Apparently the reversal of a cell reconditioned it for a later cycle. The reversal of a cell was also the cause of the periodic low voltages at the 350 A load. However, during the course of cycling, the same cell was not always the limiting one. Reference electrode readings were taken in an attempt to determine if only one electrode was limiting. In general, the nickel electrode reversed first, however, the zinc electrode also reversed voltage very soon thereafter. However, because of the wide variability of conditions under which the low pulse voltages occurred and also their unpredictability, it is impossible to ascribe a cause for this most puzzling behavior. Deep cycling was the only treatment that appeared to eliminate the low voltage pulses for any length of time. However, its effect did not last for more than 1100 Ah of cycling.

The deep cycle capacity data for Battery #2H are shown in Table III. Examination indicates that the battery did not suffer any significant loss of capacity due to cycling at a low charge potential. However, charging at 7.3 V resulted in a slightly higher state-of-charge than charging at 7.2 V. Capacity maintenance with cycling was excellent for this battery, with more than 85% of initial capacity attained after 16,710 Ah output (equivalent to 92,000 cycles).

Table III. Capacity Maintenance of Advanced, Eagle-Picher, High Rate Ni-Zn Battery #2H

Total Ah Delivered	Charge Voltage	Capacity(Ah)*	Average Discharge Voltage
Initial	--	24.0	6.3V
3,600	7.2	18.2	6.4V (1)
5,850	7.2	20.3	6.3V (1)
8,500	7.3	22.7	6.3V
16,710	7.3	20.4	6.2V
21,500	7.3	12.3	6.3V (2)
21,512	5.5	18.2	4.7V 3 cells only
21,530	--	38.0	0.5V residual zinc capacity
21,568	5.5	9.0	4.7V
21,577	5.5	11.3	3.0V 2 cells only, 2nd cell shorted
26,370	3.65	10.0	2.8V (1) "
26,380	3.65	12.0	2.9V
26,400	Cells shorted after overnight stand		

*Batteries discharged at 14A to 5.0V; charged at 4A for 6.5 hours.

(1) Water added after cycle.

(2) KOH added during charge, one cell apparently shorted.

The first failure in Battery #2K occurred when one cell was discovered to have shorted at 21,500 Ah during the deep cycle run. A series of deep cycles were then run in an attempt to recondition the battery and possibly break the short circuit. This did not prove feasible and, in fact, continued deep cycling only resulted in the short circuiting of another cell.

The two remaining cells were then returned to the vehicle simulation regime. However, the load module used for the vehicle cycling test was unable to maintain a constant current of 350 A at input voltages of less than 2.5V. Therefore, in order for the total Ah delivered per day with 2 cells to be the same as with 4 cells, it was necessary to increase the frequency of the high rate pulse from once every 30 minutes to once every 15 minutes. This change maintained the total Ah delivered per day relatively constant at approximately 260-280 Ah per day. At 26,000 Ah the voltage at the 55 A load was 3.18 V (1.59V/cell), and at the 350 A load (final current approximately 200 A) was 1.87 V (0.93 V/cell). These output voltages were considerably below those obtained earlier in the life of the battery and below the voltage considered acceptable for hybrid vehicle use. Cycling was terminated at 26,370 Ah and several deep cycles were run, as indicated in Table III. At this point Battery #2H had only half its initial capacity and had suffered considerable loss in voltage. The battery was then subjected to failure analysis.

Cycle Life Data for Advanced, High Rate Design, Energy Research Corp. 4 Ah, Ni-Zn Batteries

High rate 4 Ah Ni-Zn cells having a theoretical capacity of 5.8 Ah and an initial capacity of 4.4 Ah were received from Energy Research Corp. (ERC). These cells had non-sintered nickel electrodes. Because of the difficulty in manufacturing a pin-hole free, thin inorganic separator, these cells were made with a 1 turn sausage casing separator. The specific construction details of these cells are given in Table IV. Particularly interesting was ERC's ability to manufacture very thin positive and negative electrodes, which made a high surface area possible.

Table IV. Battery Design Parameters for Energy Research Corp., High Rate, 4 Ah Ni-Zn Cells

Rated Capacity (Ah)	4.0
Initial Capacity (Ah)	4.4
Positive Electrode: (Non-sintered type)	number 16 size (inches) 2 3/8 x 1 7/8 x .0165
Negative Electrode:	number 17 size (inches) 2 3/8 x 1 7/8 x .008
Theoretical Capacity (Ah)	14
Separator (Pellon/Fibrous Sausage Casing) (going from positive to negative electrode)	
Active Area	133 in^2
Weight	3/4 lb

A 5-cell battery was constructed and started on cycling after an initial cycle. Because of the high surface area available with these cells, it was decided to cycle them at an accelerated rate. The high current pulse was 100 A, and the lower current pulse was 16 A. These currents are approximately 66% higher than those based on a straight capacity ratio with the 24 Ah high rate design. At the high rate (100 A), the power density of this battery exceeded 200 Wh/lb.

The performance of this battery on the 50-second power test is shown in Figure 15. The voltages obtained (1.29 V/cell at the end of 50 seconds, after 420 Ah of cycling) compared favorably with the 1.2 V/cell obtained from Battery #2H after 2300 Ah of cycling. The current density for the ERC 4-Ah cells was 0.75 A/in^2 at 100 A, while for Eagle-Picher Battery #2H it was 0.8 A/in^2 at 350 A. This power test data appears to indicate that the use of a non-sintered nickel electrode for hybrid vehicle service would not cause any significant voltage loss. However, after a total 1300 Ah output, only 15-20 seconds were obtainable on the power test above 1.0 V/cell. Deep cycling was effective in improving the power test performance. Nevertheless, the battery, after 1300 Ah output, was never capable of meeting the full 50-second power test requirement. These power test results, however, were not significantly different from those obtained with the sintered nickel electrodes.

The voltage characteristics of the battery during life cycling are given in Table V. Based on the capacity available in the battery, the life obtained was equivalent to 32,000 Ah for the full sized Eagle-Picher high rate battery which was cycled for a maximum of 26,400 Ah. At the completion of cycling, a failure analysis was performed and will be discussed later.

Table V. Performance of 5 Cell, Energy Research Corp., 4 Ah Ni-Zn Battery

Ah	Voltage @ 100 A* Battery(0.75 A/in^2)	Voltage @ 100 A* Cell	Voltage @ 16 A* Battery(0.12A/in^2)	Voltage @ 16 A* Cell	
65	7.28	1.46	8.9	1.78	
140	7.23	1.45	8.83	1.77	
500	7.08	1.42	8.78	1.76	
650	6.97	1.39	8.77	1.75	
875	6.90	1.38	8.77	1.75	
936	7.01	1.40	8.80	1.76	(1) (2)
1010	6.96	1.39	8.80	1.76	
1382	6.75-6.25	1.35-1.25	8.73	1.74	(3)
1814	6.35-6.00	1.27-1.20	8.60	1.72	(1)
2388	5.5	1.1	8.58	1.74	
2540	6.90	1.38	8.72	1.74	(1) (2)
2760	5.48	1.37	6.92	1.73	one cell shorted
2960	4.01	1.35	5.17	1.72	2nd cell shorted
3034	4.02	1.34	5.14	1.71	
3470	3.96	1.32	5.15	1.71	
3770	3.94	1.31	5.15	1.71	
4283	3.94	1.31	5.16	1.72	
4456	3.90	1.30	5.12	1.71	
4535	4.11	1.37	5.15	1.71	(2)
4744	4.13	1.38	5.18	1.72	
4819	3.85	1.28	5.05	1.68	High overcharge 8-15%
5108	2.4	0.80	5.02	1.57	
5313	2.1	0.70	5.0	1.66	

*Batteries charged at 9.2 V (1.84 V/cell)

(1) After KOH addition

(2) After deep cycle

(3) Variation in EOD voltage at 100 A load

Cycle Life Data for Advanced, High Rate Design, Energy Research Corp. 20 Ah, Sealed Ni-Zn Batteries

Two full size 20-Ah batteries constructed in the same cell cases as the BB-674( )/U were received from Energy Research Corp. at the very end of this project. These batteries incorporated some of the design features that could

result in a better nickel-zinc battery for hybrid service. Table VI gives their specific design parameters. The batteries were sealed, with a 60 psi valve, to eliminate maintenance. The separator system incorporated inorganic material as an interseparator. One layer of cellophane was included to stop zinc penetration, which would occur if only the ERC inorganic material was used. Two Ag-Hg third electrodes of sufficient area to permit a continuous overcharge of approximately 5 A were incorporated in these batteries.

Only initial data were obtained with these batteries and results indicated possible problem areas. Initial voltages obtained were considerably lower than expected: 1.66 V/cell at 55 A, and 1.08 V/cell at 350 A. The batteries were charged at 7.3 V (1.83 V/cell) and received approximately 10% overcharge. The heavy potted construction, employed to prevent battery swelling, has resulted in greatly increased weight and poor heat transfer characteristics. Further evaluation of these batteries could not be carried out because of the completion of the test period.

Table VI. Battery Design Parameters for Energy Research Corp. 20 Ah Sealed Ni-Zn Batteries

Initial Capacity (Ah)	20
Positive Electrode (Non-sintered type)	Number - 16 Size - 5 1/8" x 2 7/8" x 0.018"
Theoretical Capacity (Ah)	24.5
Negative Electrode	Number - 16 full, 2 half on ends Size - 5 1/8" x 2 7/8" x 0.023" (full) 0.013" (half)
Theoretical Capacity (Ah)	120
Separator - ERC 2001/PUDO 300/ERC 2001 (going from positive to negative electrode)	
Third Electrode	Silver-Mercury Type 2 each 5 1/2" x 1 1/8"
Pressure Relief	50-60 psi
Active Area	472 in^2
Weight	9.1 lb (potted)

Battery Heat Generation and Removal

A key consideration in the design of a full size hybrid battery for vehicle service is the amount of heat which will be generated and, therefore, the amount of conductive structure which will be required to remove it.

Battery heat generation may be closely approximated by taking the difference between the electrical input and output. It will be assumed, for the purpose of this calculation, that all the gas generated by overcharge is recombined. If any gas is vented from the battery, then the amount of heat generated would be somewhat lower than that shown by the calculation in Table VII.

Table VII. Calculation of Battery Heat Generation

	BB-674( )/U #2 (a) @ 3,000 Ah output	High Rate Battery #1H (b) @ 3,000 Ah output
Energy Input/Hour	7.4 V x 11.8 Ah = 87.4 Wh/h	7.4 V x 11.7 Ah = 86.6 Wh/h
Energy Output/Hour	6.75 V x 9.5 Ah = 64.1 Wh/h 4.7 V x 2.1 Ah = 9.9 TOTAL 74.0Wh/h	6.9 V x 9.5 Ah = 65.5 Wh/h 5.6 V x 2.1 Ah = 11.8 77.3Wh/h
Heat Output	87.4 - 74.0 = 13.4 Wh/h = 45.7 Btu/h	86.6 - 77.3 = 9.3 Wh/h = 31.7Btu/h

(a) Data from Figure 8

(b) Data from Figure 11

NOTE: Voltages are average discharge voltages.

At the calculation points, which have been chosen to represent approximately steady state conditions, where all the uncharged zinc oxide has been charged, a BB-674( )/U cell would evolve 11.45 Btu/h, while the high rate design cell would evolve only 7.93 Btu/h. Heat generation could be further lowered by increased plate area and conductive members. An even more effective way of reducing heat was a reduction in the charging voltage. When battery #2H was charged at 7.2 V at 5,000 Ah output, the calculated heat generation was only 6.8 Btu/cell/h. Therefore, based on a heat generation of 7.93 Btu/cell/h, a full size 120-cell battery would evolve 952 Btu/h on the simulated regime. This amount of heat could be easily removed in vehicle operation. As the battery ages, heat generation will increase approximately 70% at the point when the battery is no longer capable of meeting its power requirements. This amount of heat (1700 Btu/h) can still be easily removed.

Based on a very limited number of runs of the ERC sealed 20 Ah battery, it would appear that a sealed battery with uncharged zinc-oxide

may evolve twice as much heat as a comparable vented one. This is due to the fact that the percent overcharge remains at approximately 10% for the sealed battery, while in a vented battery the overcharge percentage drops from 8-10% to 1-2% after all the reserve zinc oxide is charged.

Gas Generation

Several measurements of gas generation, by individual cells in the various batteries tested, were made during the course of this project. Gas generation was found to be a function of the state-of-charge of the battery (zinc electrode) and the percent measured overcharge. Typical gas evolution rates were 50-100 cc/h/cell. In general, except for the initial 1000-2000 Ah of cycling, the gas evolved is 1/3 oxygen and 2/3 hydrogen. During the initial cycles the gas evolved is mainly oxygen. Calculations of actual vs theoretical gas have indicated that, in the typical vented nickel system, negligible recombination of gases occur. With a low charging voltage, the percent overcharge can be reduced, and hence the amount of gas generation and water makeup required.

Battery Failure Analysis on Standard and Advanced Eagle-Picher Ni-Zn Batteries

Upon the completion of cycling, individual cells were dissected and failure analysis was conducted. At a minimum, this analysis consisted of a visual examination and measurements of the positive and negative electrodes and separator, and a carbonate analysis of the electrolyte. Table VIII lists the tests performed on each battery and the results. In addition, electrodes were removed from BB-674( )/U #1 after 16,500 Ah and built into test batteries with new counter electrodes and separator. Table IX lists the various electrodes evaluated and their performance.

From the results shown in Table IX it can be seen that the nickel electrode has suffered no apparent loss in capacity due to 16,500 Ah of cycling, in fact, it may have even increased in capacity. The zinc electrode on the other hand appears to be about 25% below its initial capacity and has some drop in voltage. Because of the large excess of zinc capacity originally available, sufficient zinc capacity should exist to enable the battery to deliver rated capacity.

Table VIII. Failure Analysis of Eagle Picher Ni-Zn Batteries

Battery	Examined at Ah output	Final Batt. Capacity	Electrolyte KOH%	Electrolyte K_2CO_3%	Separator Appearance	Zn Electrode Appearance	Nickel Electrode Appearance
BB-674 #1	13,000	17 Ah See Fig 9	3	33	No zinc penetration. Limited degradation of FSC at edges and above plates; See Fig 16.	Negligible shape change. See Figures 17a,b.	Excellent condition. No blisters, cracks, or excessive expansion. See Figure 19.
BB-674 #2	13,000 (Shorted)	17.3 Ah See Fig 10	10	23	As above	Approximately 20% zinc electrode shape change.	No cracks or blisters. Edge curling opposite areas of zinc shape change.
High Rate Battery #1	12,400 (Shorted)	15.4 Ah	-	-	Zinc dendrites in negative pellon bag. FSC attacked at bottom, top and edges. Cause of short not apparent.	Approximately 10-15% zinc electrode shape change.	As above
High Rate Battery #2	26,400 (Shorted)	12.0 Ah	6	20	Attacked at edges and top. Possible short at positive tab area.	Less than 15% zinc electrode shape change. See Figures 18a, b	No curling or cracking. See Figures 20a,b

Table IX. Capacity Analysis of Nickel and Zinc Electrodes After 16,500 Ah

Type	Cycle 1 Ah_o	Cycle 1 $V_{avg.}$	Cycle 2 Ah_o	Cycle 2 $V_{avg.}$
1 old Zn, 2 old Ni	5.1	1.55	5.0	1.53
1 old Zn, 2 new Ni	5.1	1.48	4.2	1.47
1 new Zn, 2 old Ni	6.6	1.58	5.8	1.58
1 new Zn, 2 new Ni	6.0	1.56	5.3	1.56

NOTE: Batteries charged at 1.0 A for 9 hours; discharged at 3.0 A to 1.0 V. Electrode area = 23.4 in^2; theoretical capacity 6.4 Ah, BB-674( )/U Battery #1

The failure analysis data given in Tables VIII and IX, as well as Figures 16, 17, and 18, clearly indicate that life is limited by shorting and separator degradation rather than zinc electrode shape change. Even though the cellulosic separator is not completely oxidized when it is between the electrodes, it is a major source of carbonate contamination of the electrolyte. High carbonate contents in the electrolyte appear to confer one benefit in that the amount of zinc shape change is reduced. This occurs because zinc solubility is lower in carbonated solutions. Zinc electrode shape change was found to be very low compared to the total amount of energy delivered because of two other reasons. The first was the Teflonated zinc electrode design and, second, the nature of the pulse loading applied.

The nickel electrode, as shown in Figures 19 and 20, suffered negligible change during up to 26,450 Ah of cycling and maintained full or even increased capacity. Action must be taken to protect the tab area (See Figure 20), particularly on thin plate cells to prevent high spots which can accelerate shorting. In general, it can be stated that the nickel electrode should present no problem in a hybrid vehicle regime.

Battery Failure Analysis on Cells with Non-Sintered Positive Electrodes

Energy Research Corp. 4-Ah high rate cells were dissected after 5,300 Ah of cycling. The design of these cells was given in Table IV. The failure analysis indicated that the 1 turn of fibrous sausage casing used as the separator was penetrated by zinc dendrites. The separator was attacked at the top and sides. The nickel electrode was undamaged but had swelled from 0.0165" to 0.0265". This amount of expansion is considered relatively normal for the non-sintered nickel hydroxide electrode. Subsequent to the building of these cells, Charkey (11) reported an improved nickel hydroxide preparation process which resulted in less expansion of the positive plate with cycling. The zinc electrodes in these cells had approximately 10% shape change. Based on these observations, it can be concluded that a non-sintered nickel electrode can be used in a Ni-Zn battery for hybrid vehicle service. One turn of fibrous casing, however, would not be sufficient separation for the desired life.

Cells with Inorganic Separators

Several 40 Ah sealed silver-zinc cells and zinc electrodes made with Astropower inorganic separators were made available for this program by NASA-Lewis. The silver-zinc cells had been activated for more than one year and had also been heat sterilized. One battery was put on deep cycling to determine its capacity maintenance characteristics. The regime consisted of a charge at 2.0 A to 2.05 V followed by a 10 A discharge to 1.2 V. The results obtained are shown in Figure 21.

Because of the good results obtained for the first 25 cycles and hence the apparent excellent shape change characteristics of the Astropower electrode and the stability of the separator, a 3 plate Ni-Zn cell was constructed using the bagged Astropower zinc electrode and 2 cut down nickel electrodes from a BB-674( )/U battery. The charge-discharge voltages for this cell are shown in Figure 22. The discharge voltage obtained was considerably lower than comparable standard cells. It had previously been reported that the Astropower separator and electrode might require several cycles and/or sterilization to be completely wetted and therefore have a low internal resistance. One cell was built with Astropower zinc electrodes and separator and subjected to 24 hours sterilization at 110°C. Another cell was built using the Astropower zinc electrode with a fibrous casing separator. Based on the discharge voltages obtained from the 3 cells described, it was determined that the sterilization treatment had a negligible effect on voltage. The cell with the casing separator had a slightly higher voltage than the other two cells, but still less than normal. Reference electrode readings indicated that the major portion of the voltage loss occurred in the Astropower zinc electrode and was probably due to the addition of KT (potassium titanate) as an electrolyte absorber to the zinc. The 3 cells were then put on a cycling regime consisting of 5 hours of charge at 1 A followed by a 1 A discharge to 1.2 V/cell. The data obtained are shown in Figure 23. Based on the results, it would appear that the Astropower separator reduced cycle life by 50% compared with a sausage casing. Sterilization of the Astropower separator and zinc electrode further reduced cycle life.

After the Astropower 40 Ah Ag-Zn cell had completed 174 cycles and had indicated short circuiting, cycling was terminated and the cell dissected. The zinc electrode had been reduced to less than 40% of its original area. The separator bags had cracked on the edges, permitting the growth of zinc dendrites and therefore short circuiting. However, the separator did not show penetration of either zinc or silver on areas opposite the electrode faces.

The Astropower separator and zinc electrodes, while having good stability in shallow depth of discharge cycling in silver-zinc cells, do not appear to have the low resistivity and stability required for hybrid vehicle operation of nickel-zinc batteries.

Sealed nickel-zinc cells containing inorganic separator material built by Energy Research Corp. were made available from another program. The inorganic separator consisted of metallic layer hydroxide inorganic materials with a Teflon binder. Two different thickness and porosity materials designated ERC1001 and ERC2001 were prepared and built into cells (4,11). When cells containing 2 layers of the thin ERC2001 separator were cycled, they shorted after approximately 40 deep cycles. Examination revealed several small spots on the separator where zinc may have penetrated. It appears, therefore, that 2 layers of the ERC2001 separator are insufficiently hole-free to prevent shorting. In addition, if sealed cells of this type are allowed to stand for even a day, in a partially shorted state, they develop considerable hydrogen pressure. The ERC2001 material is, at present, inadequate by itself as the separator for hybrid Ni-Zn batteries.

Recommended Battery Design

A proposed Ni-Zn battery for hybrid service in a 4,000 lb family type vehicle, based on present technology, should have the following characteristics:

Number of cells	120
Charge voltage (modified constant potential of 1.835V/cell)	220V
Open circuit voltage (after discharge)	210V
10kW average discharge voltage	207V
55kW average discharge voltage	165V
Maximum charge acceptability	> 30kW (130A)
Nominal capacity	20-25Ah
Active area (in^2/cell)	>500
Cell Weight	2.4 lbs each
Estimated Battery weight (Includes battery case & heat conductors)	350-400 lbs
Battery volume	2.7-3.0 ft^3
Cost (estimate only)	$1,500
Life expected (present designs)	150,000 cycles

CONCLUSIONS

High rate design conventional nickel-zinc batteries, capable of delivering up to 300 W/lb, have demonstrated a capability of up to 26,000 Ah on the hybrid cycling regime. This amount of total capacity is equivalent to approximately 150,000 cycles and is 3/8 of required life. Small 4 Ah cells have demonstrated a life equivalent to 1/2 of that required. Reliable operation above these levels cannot be attained without improved separators.

Nickel-zinc batteries can operate in hybrid service with energy efficiencies of up to 89%, which is better than competing systems.

Separators containing cellulosic material, such as fibrous sausage casing, are oxidized and convert the KOH electrolyte to carbonates under the high temperature conditions existing on the hybrid simulation regime. The oxidized cellulosic separator is then unable to prevent shorting.

Astropower type separators and zinc electrodes appear to offer no advantages for hybrid vehicle operation of Ni-Zn batteries. The ERC layer hydroxide inorganic separators tested have low electrical resistance but do not prevent shorting by zinc dendrites when they are used as the main separator.

The nickel electrode is basically unaffected by cycling even when many thousands of ampere-hours are drawn from it.

The zinc electrode suffers considerably less shape change on the hybrid regime than it would be with conventional cycling.

Modified constant potential charging, at potentials as low as 1.83V/cell, adequately maintain cell capacity, while minimizing overcharge and heat generation. This results in less frequent water additions. It is estimated that for the average driver, water would only have to be added every 6 months. A deep conditioning cycle would probably be required at about the same frequency.

Insufficient data has been generated to fully assess the effect of sealed operation. However, it does increase overcharge and temperature.

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10. T. Blickwedel, "Evaluation of Ni-Fe and Ni-Zn Batteries," Final Report, Contract DAAB 07-68-C-0102, (ECOM),General Telephone and Electronics Inc., May 1969.

11. A. Charkey, "High Energy Sealed Nickel-Zinc Batteries," First Semi-annual Report, Contract DAAB07-72-C-0114(ECOM), Energy Research Corp., January 1973.

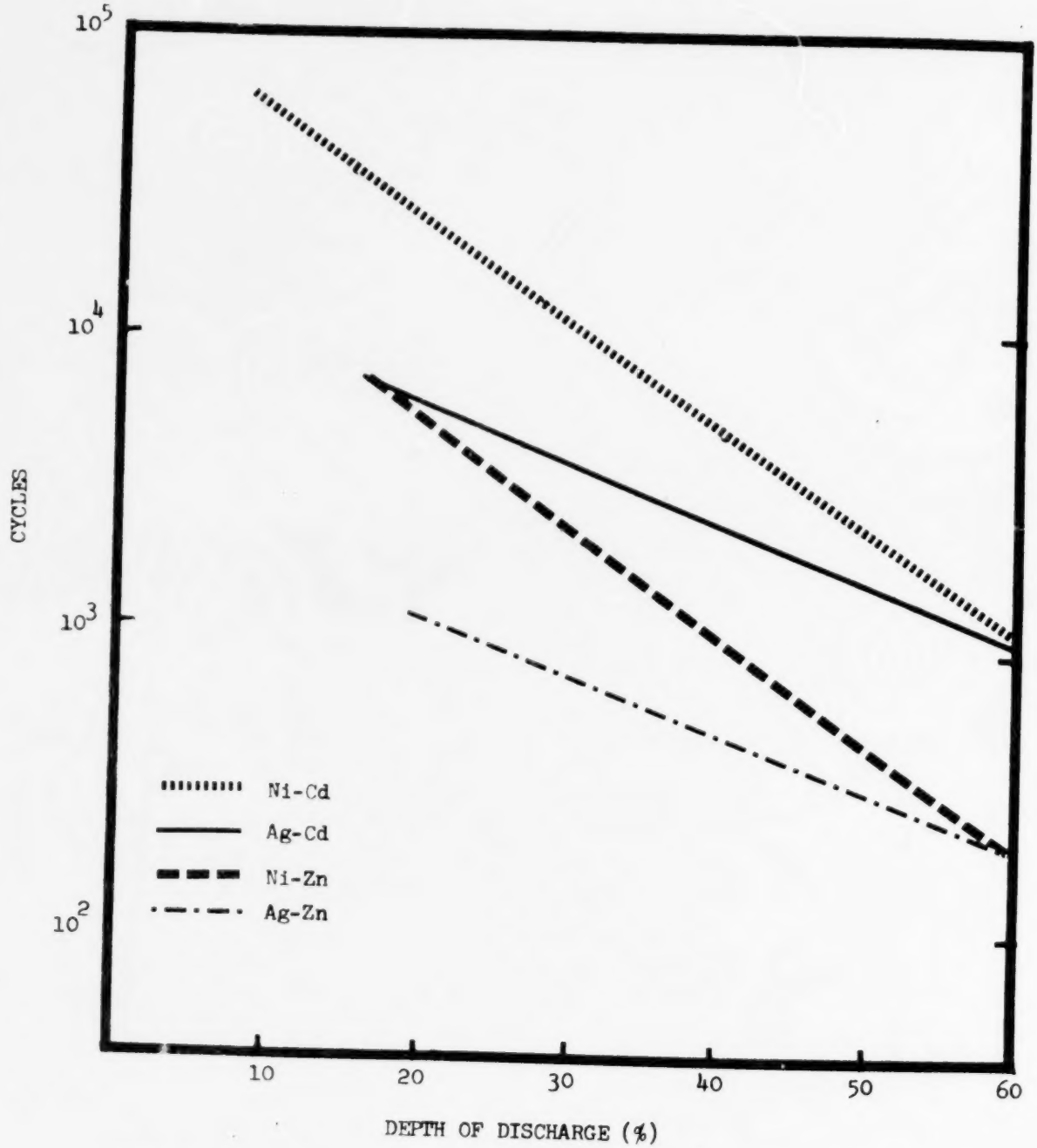

Figure 1. CYCLE LIFE VERSUS DEPTH OF DISCHARGE FOR VARIOUS BATTERY SYSTEMS

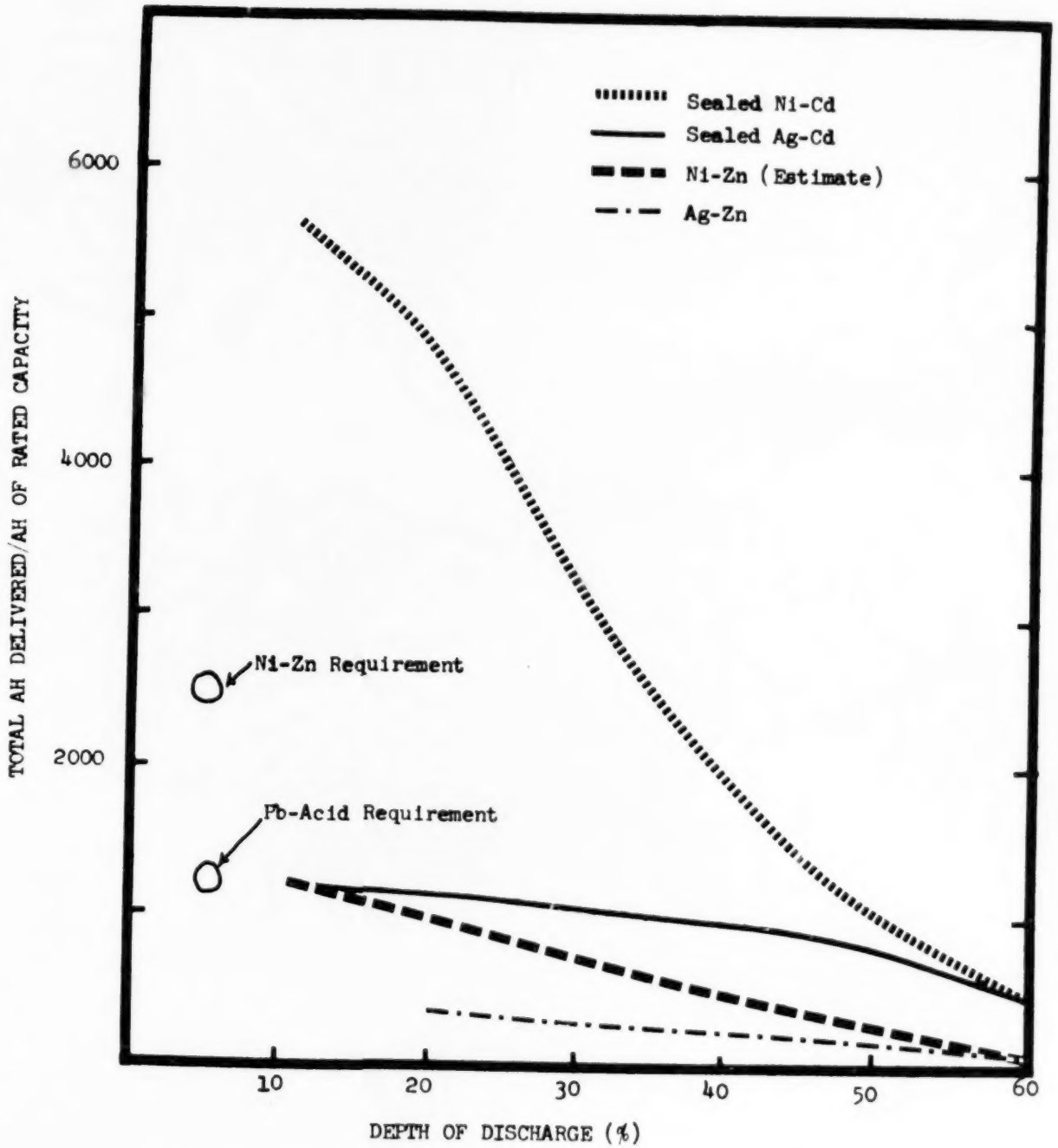

Figure 2. TOTAL ENERGY OUTPUT AS A FUNCTION OF DEPTH OF DISCHARGE

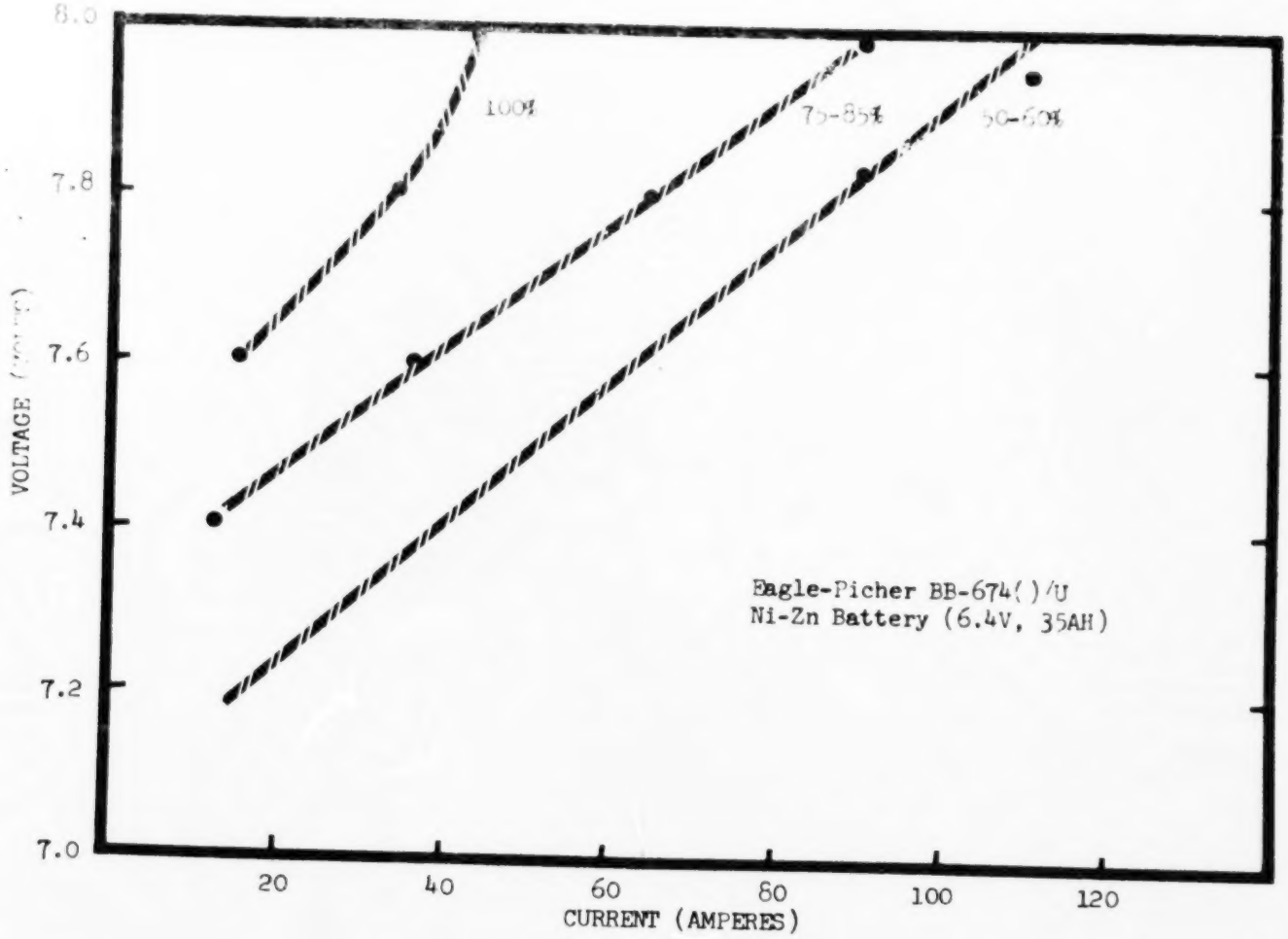

Figure 3. CHARGE CURRENT VERSUS CHARGE VOLTAGE AS A FUNCTION OF STATE-OF-CHARGE FOR STANDARD EAGLE-PICHER Ni-Zn BATTERY

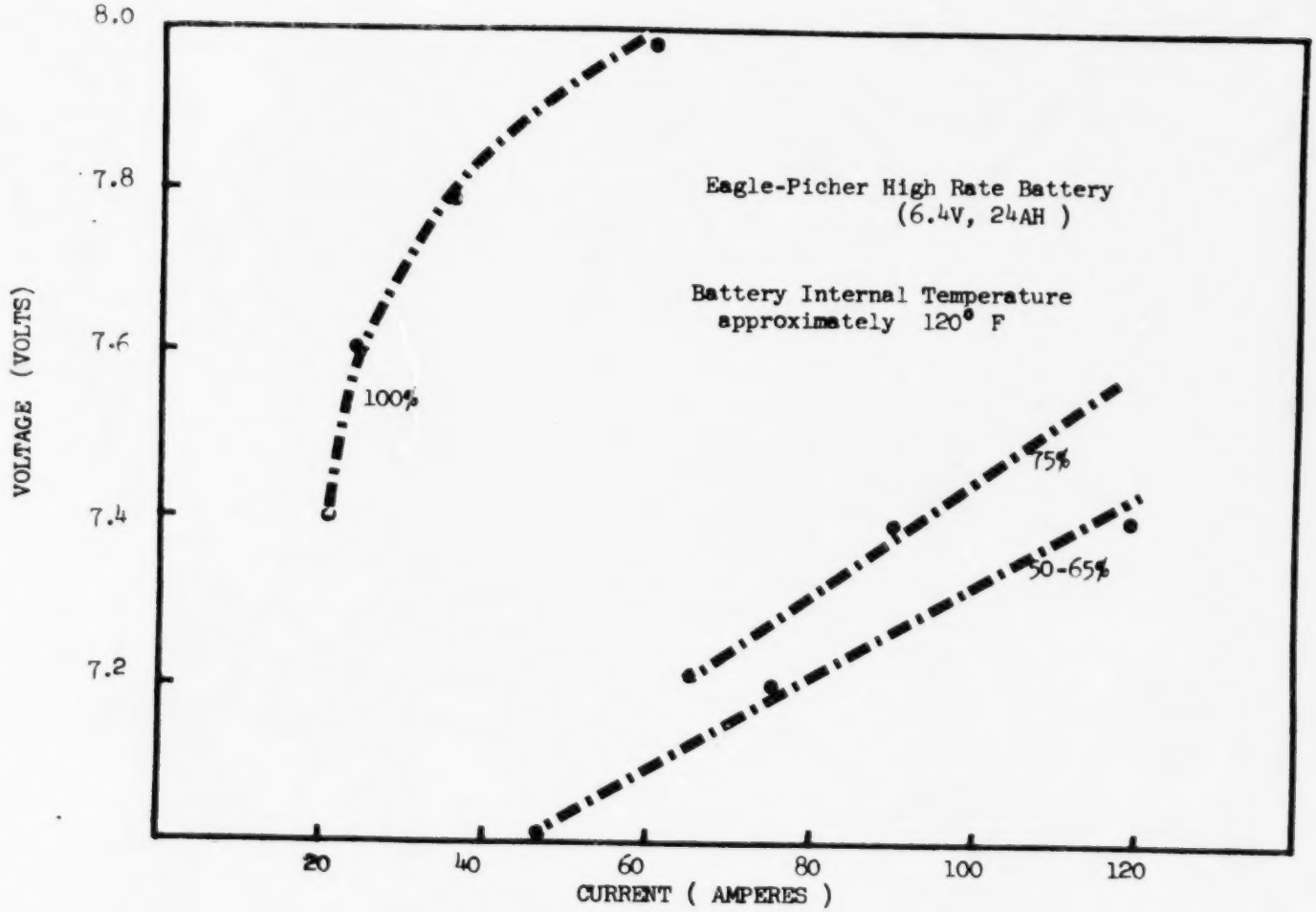

Figure 4. CHARGE CURRENT VERSUS CHARGE VOLTAGE AS A FUNCTION OF STATE-OF-CHARGE FOR ADVANCED, HIGH RATE, EAGLE-PICHER Ni-Zn BATTERY

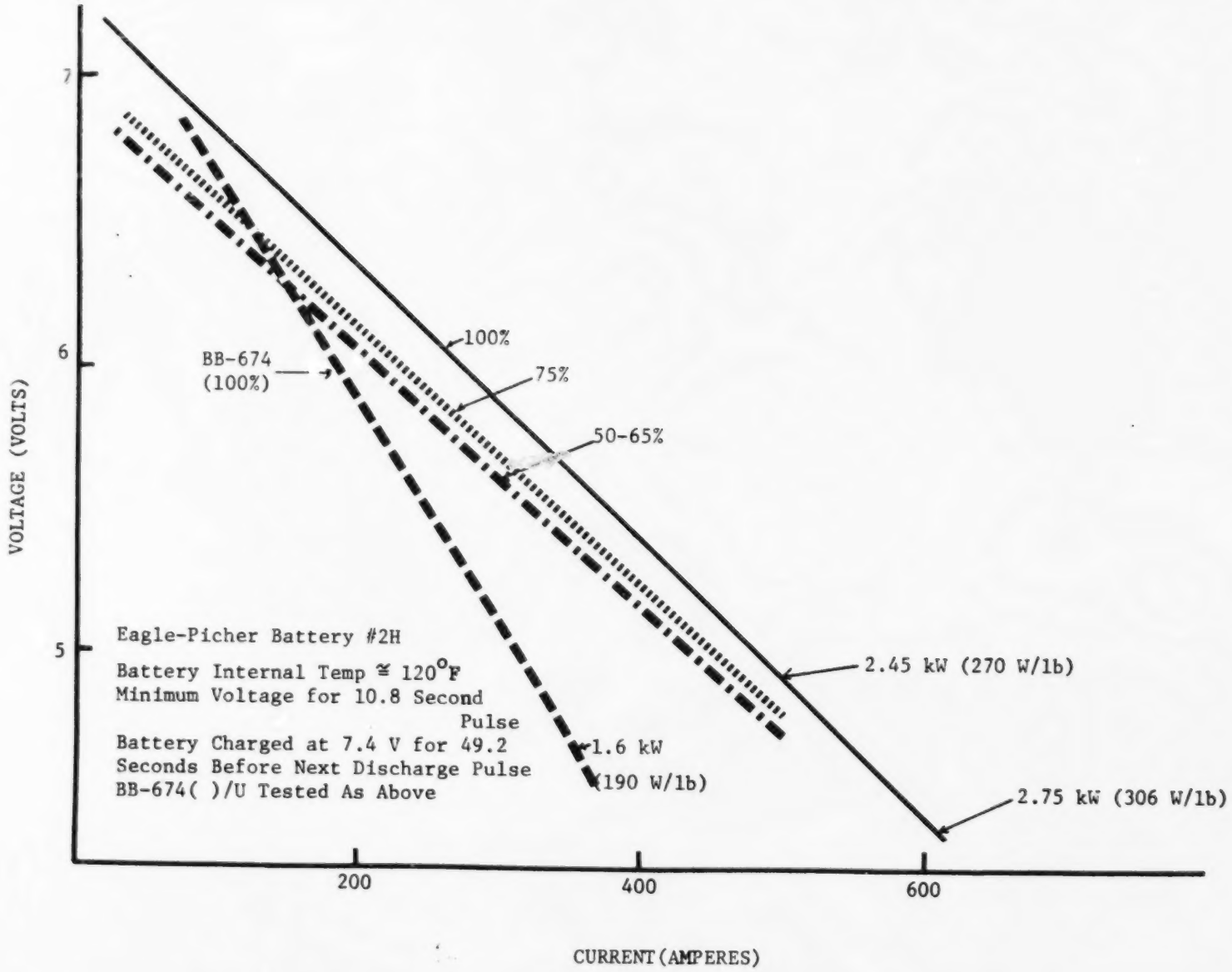

Figure 5. VOLTAGE-CURRENT CHARACTERISTICS OF HIGH RATE Ni-Zn BATTERIES AS A FUNCTION OF STATE-OF-CHARGE

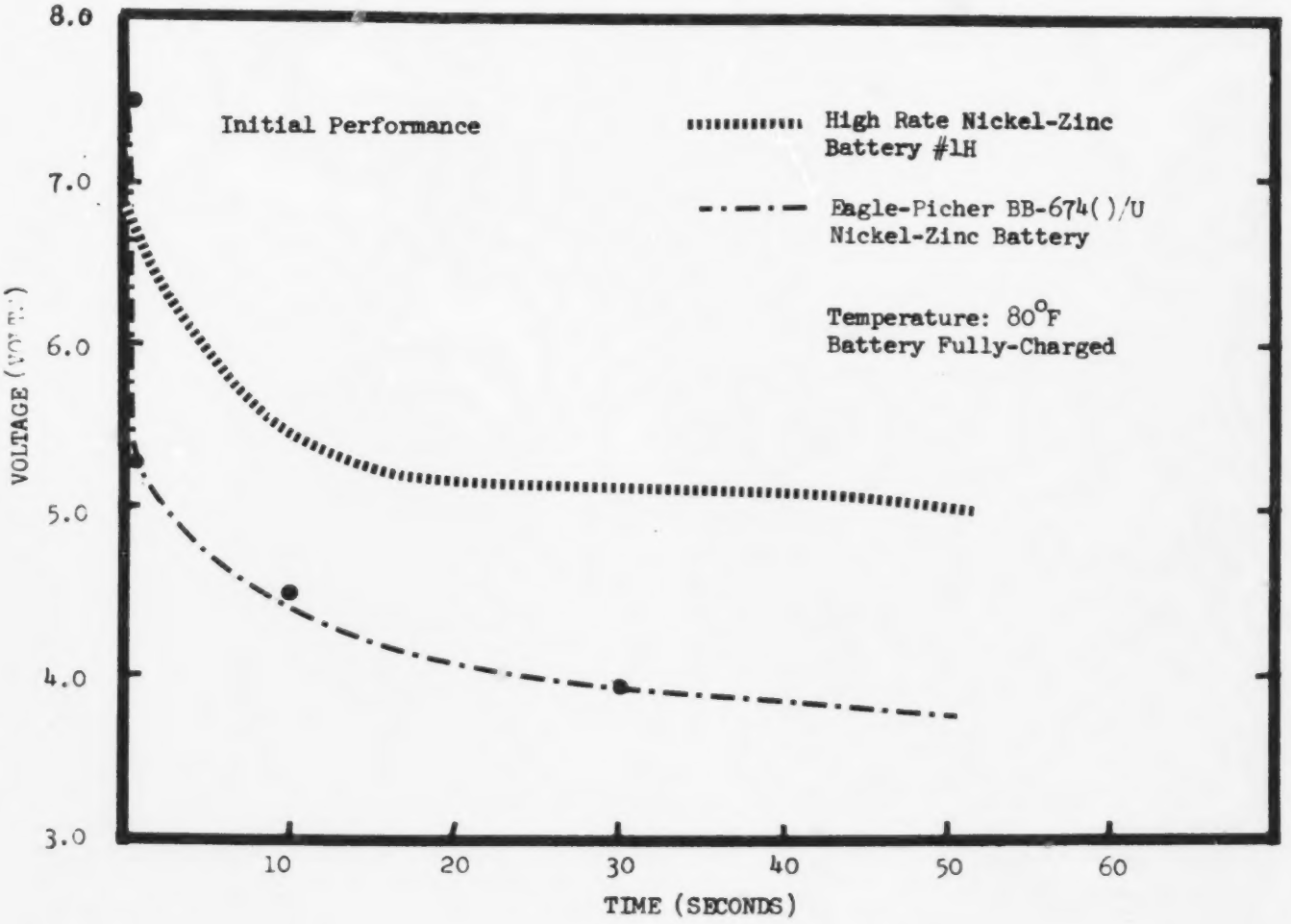

Figure 6. DISCHARGE VOLTAGE FOR 350 AMPERE LOAD

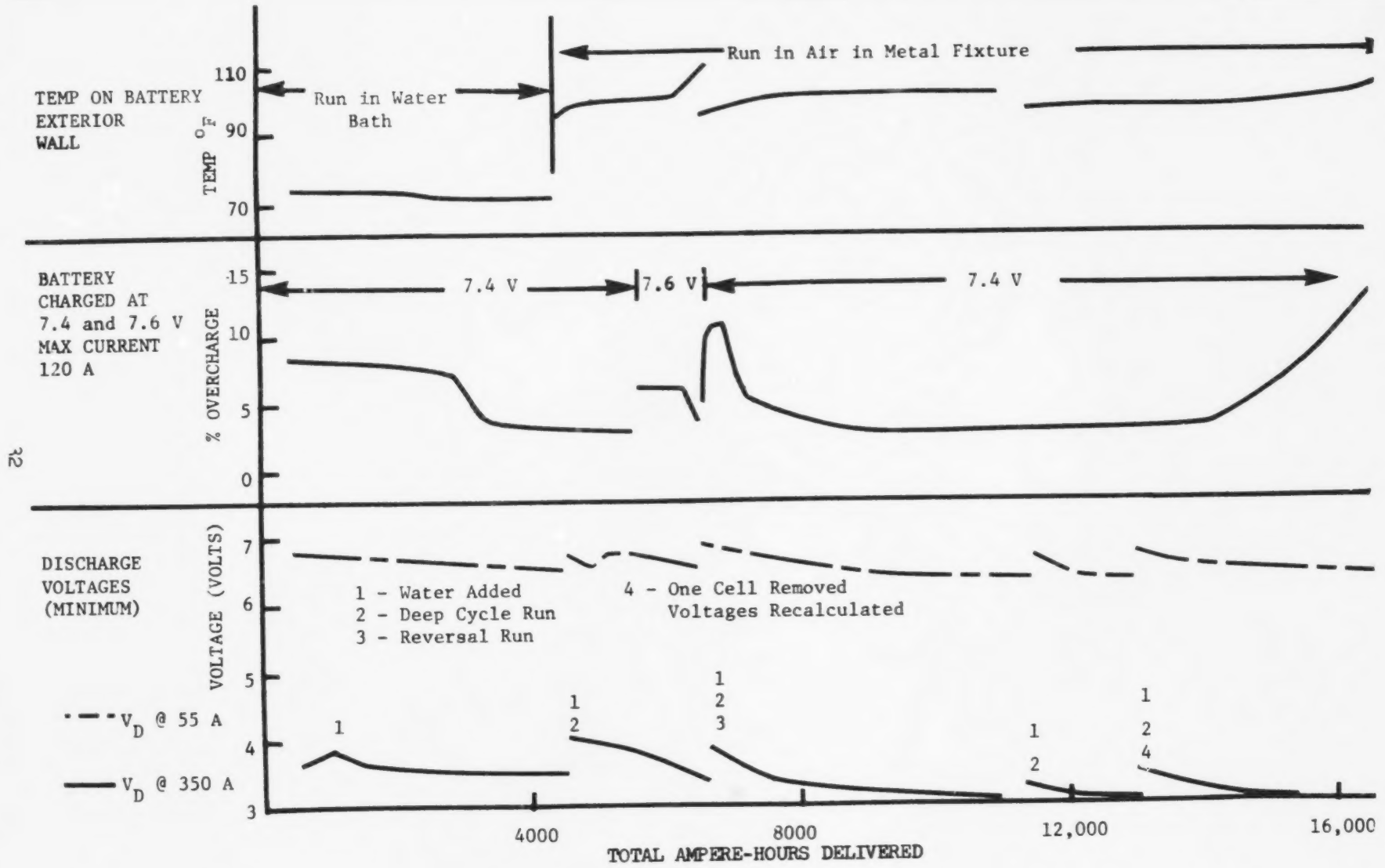

Figure 7. CYCLING HISTOGRAM FOR STANDARD, EAGLE-PICHER Ni-Zn BATTERY BB-674( )/U (#1)

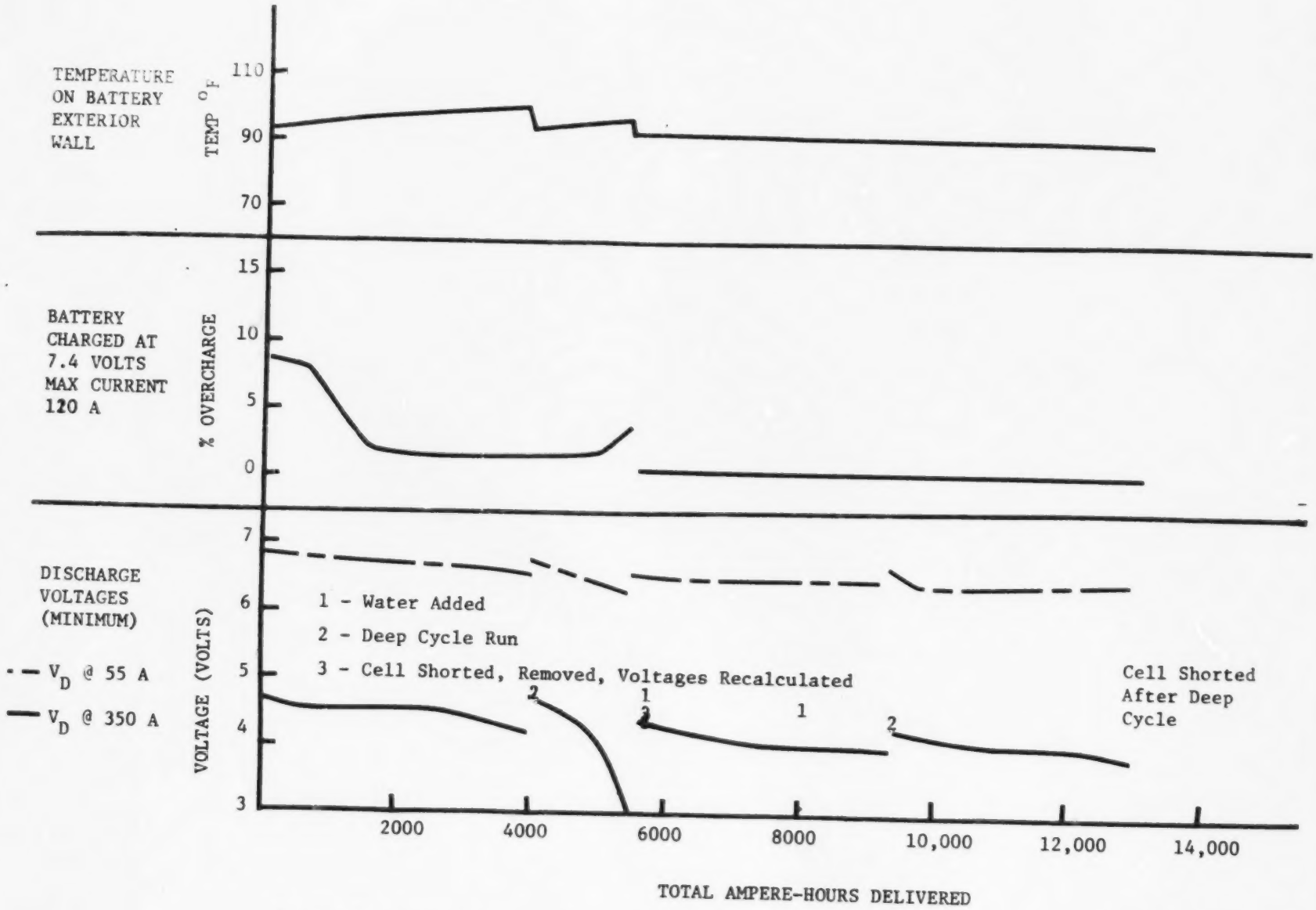

Figure 8. CYCLING HISTOGRAM FOR STANDARD, EAGLE-PICHER Ni-Zn BATTERY BB-674( )/U (#2)

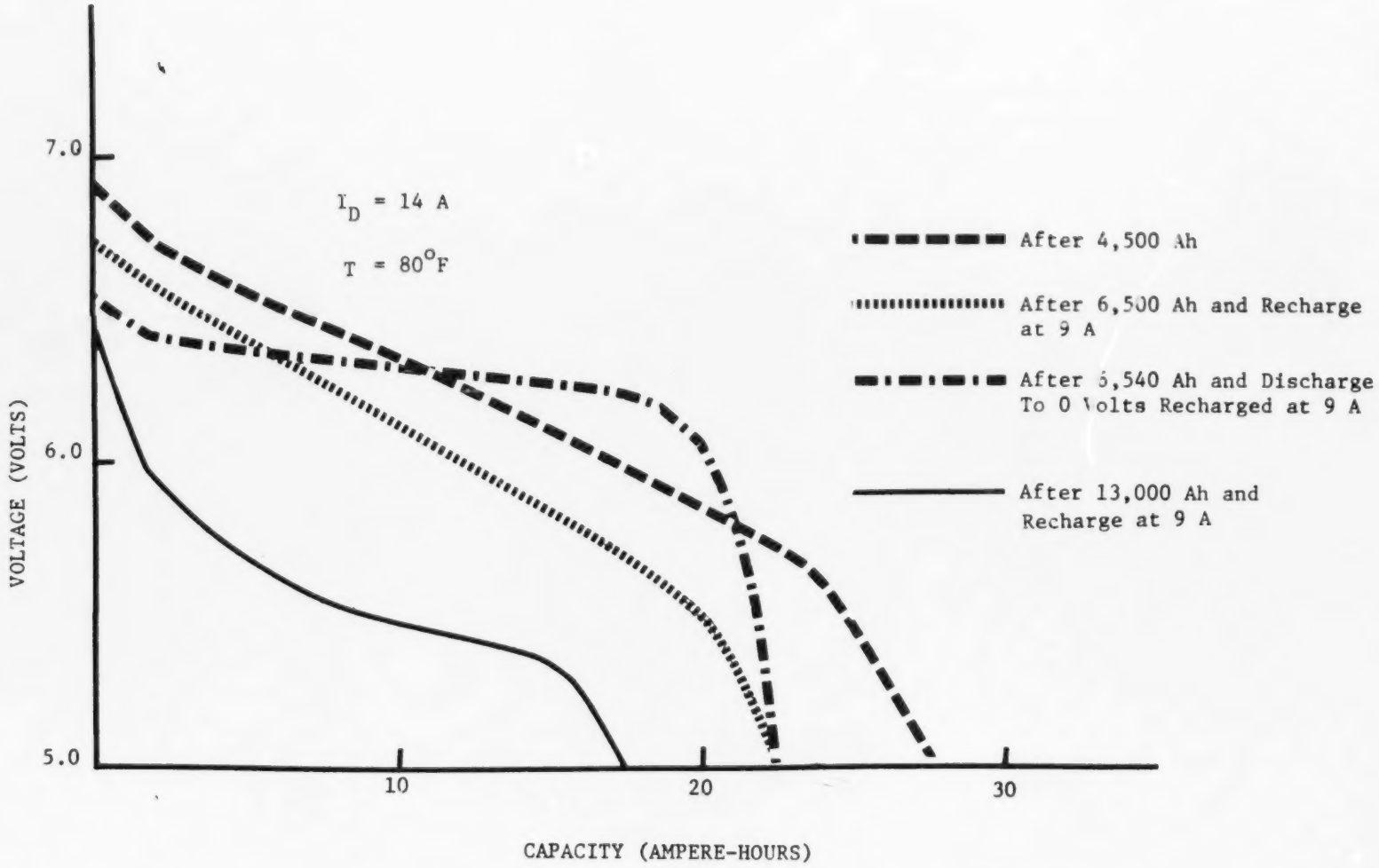

Figure 9. DEEP DISCHARGE CURVES FOR STANDARD, EAGLE-PICHER Ni-Zn BATTERY #1 AFTER PULSE CYCLING

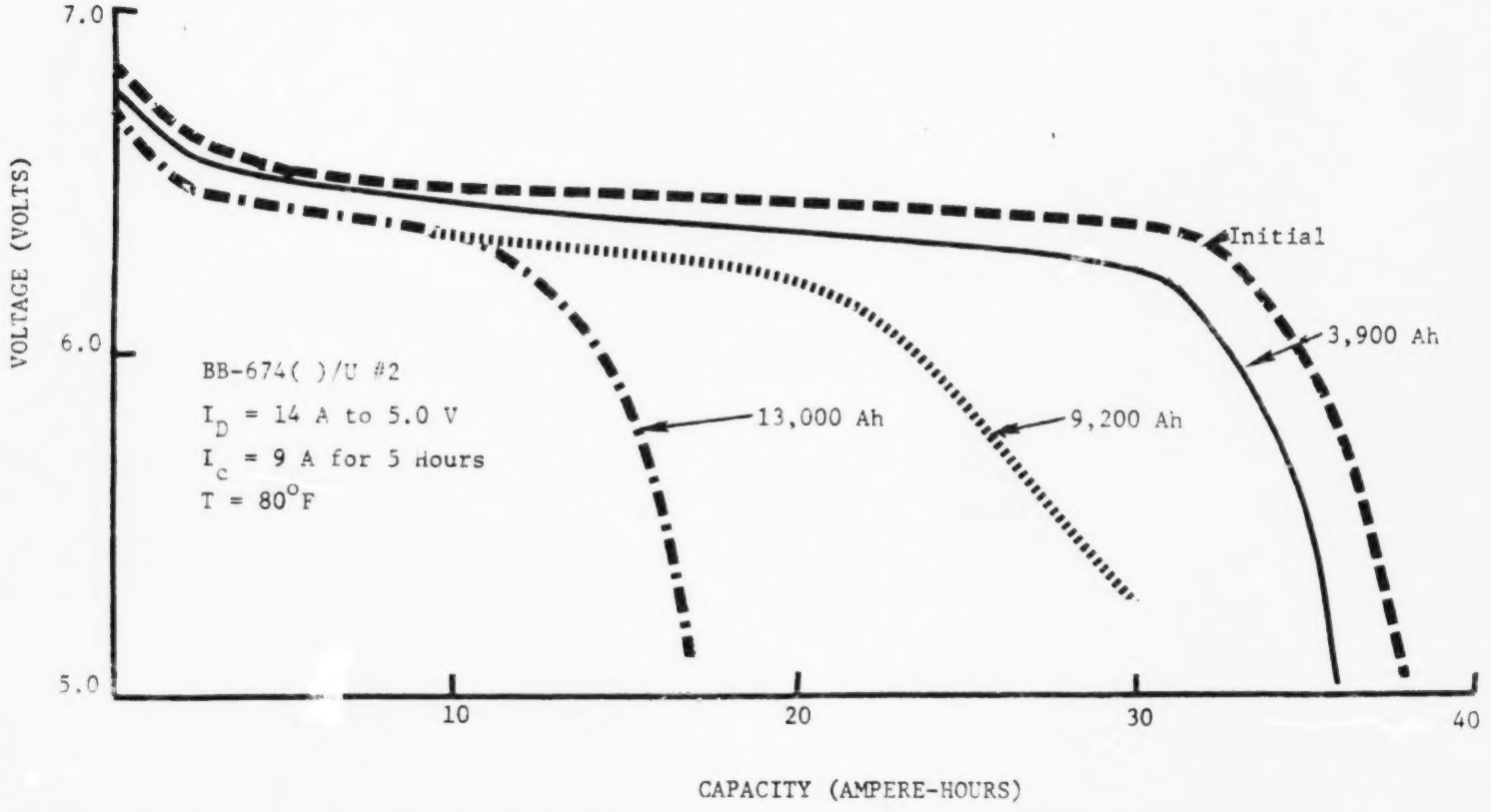

Figure 10. EFFECT OF CYCLING ON DEEP DISCHARGE CAPACITY AND VOLTAGE OF STANDARD EAGLE-PICHER Ni-Zn BATTERY #2

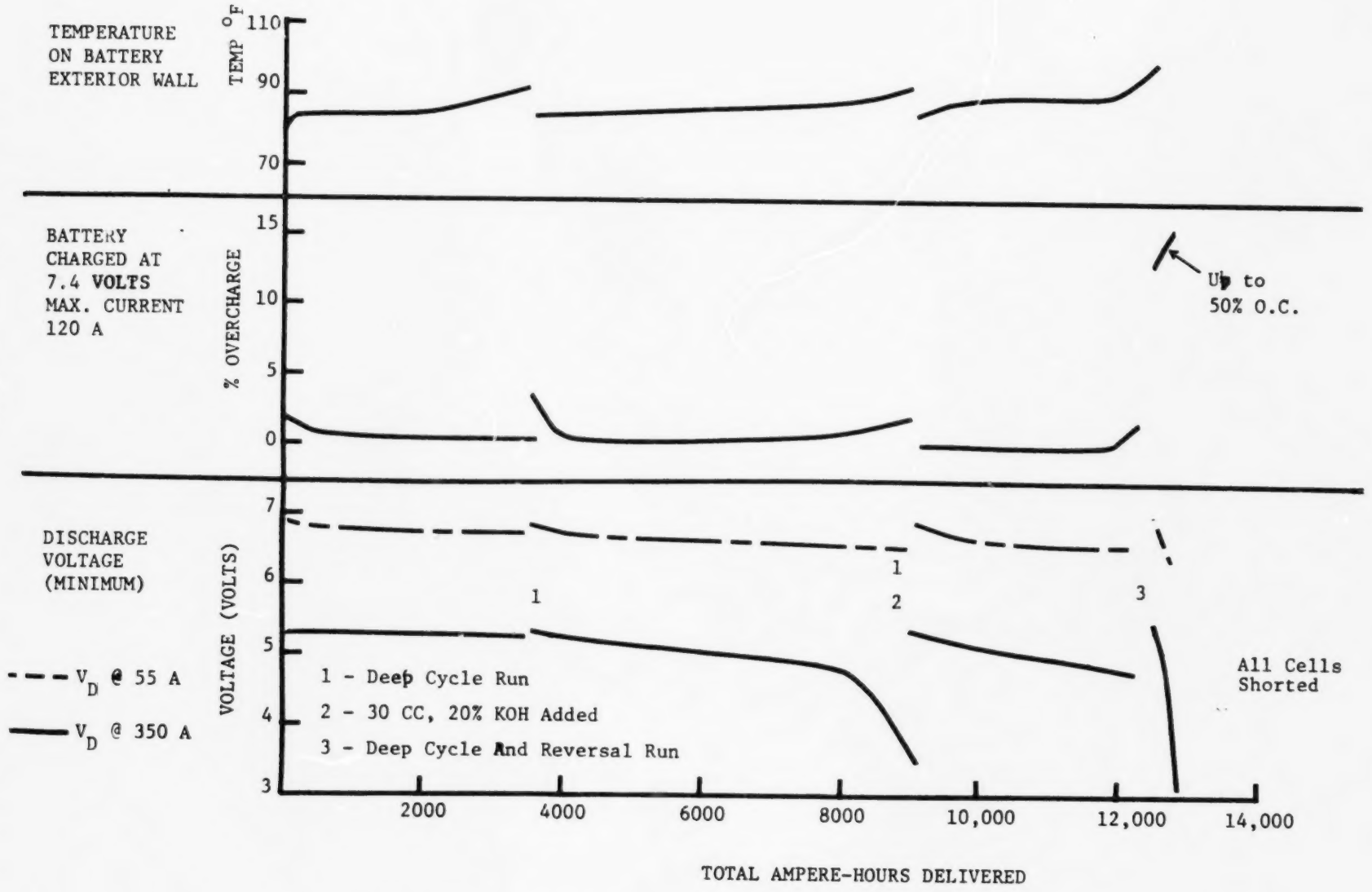

Figure 11. CYCLING HISTOGRAM FOR ADVANCED, HIGH RATE, EAGLE-PICHER BATTERY #1H

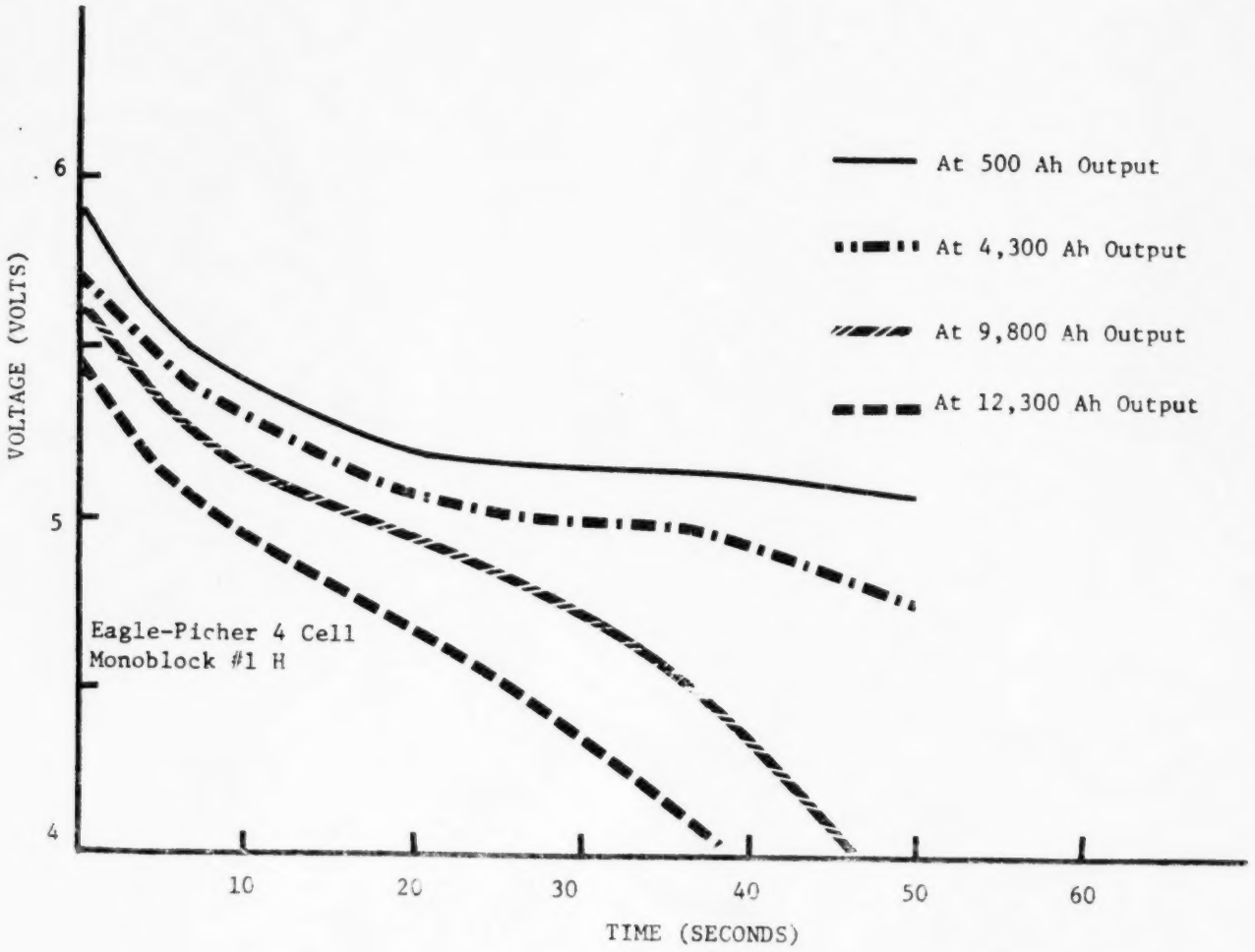

Figure 12. POWER TEST PERFORMANCE AS A FUNCTION OF LIFE FOR ADVANCED, HIGH RATE, EAGLE-PICHER BATTERY #1H

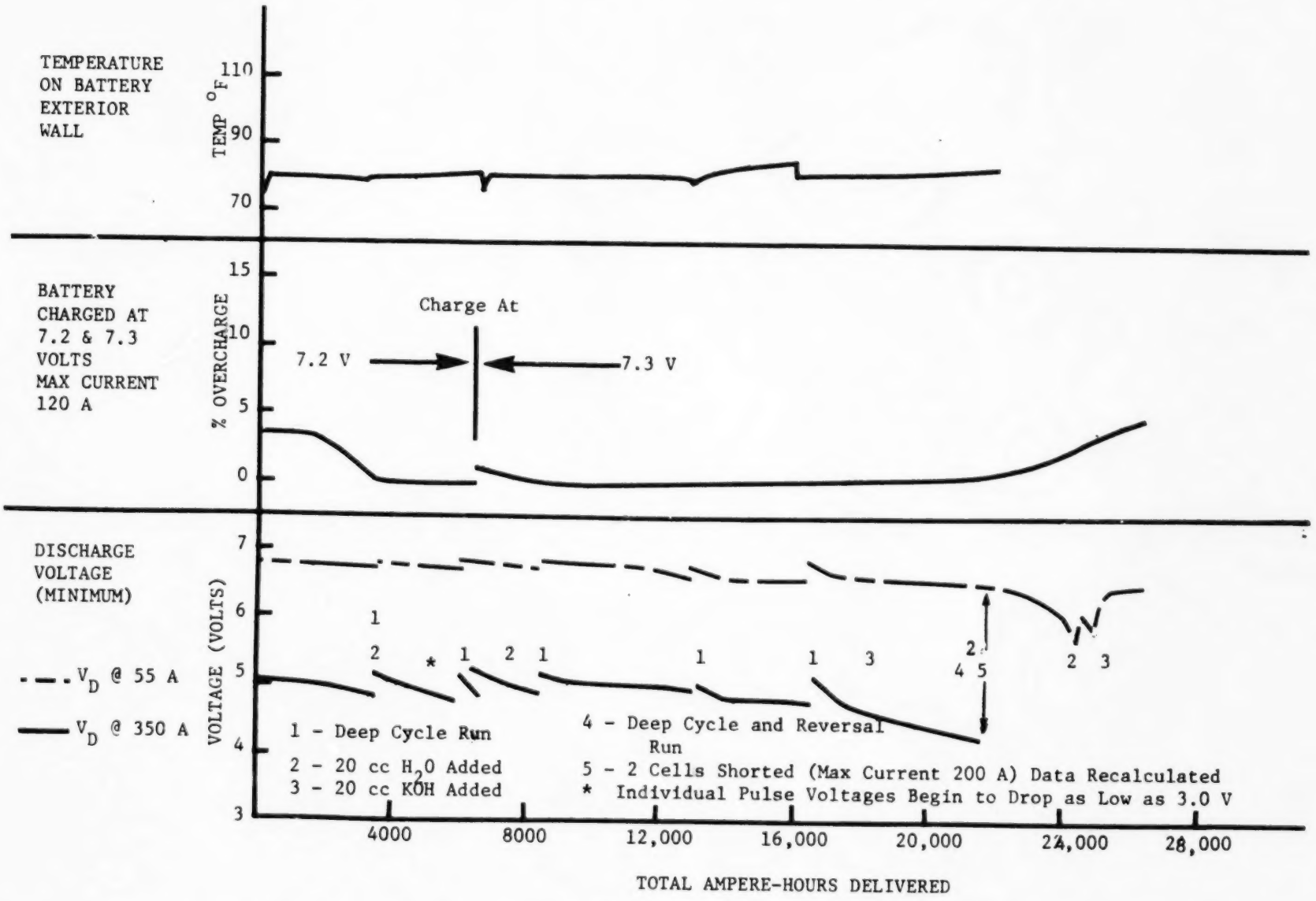

Figure 13. CYCLING HISTOGRAM FOR ADVANCED, HIGH RATE, EAGLE-PICHER BATTERY #2H

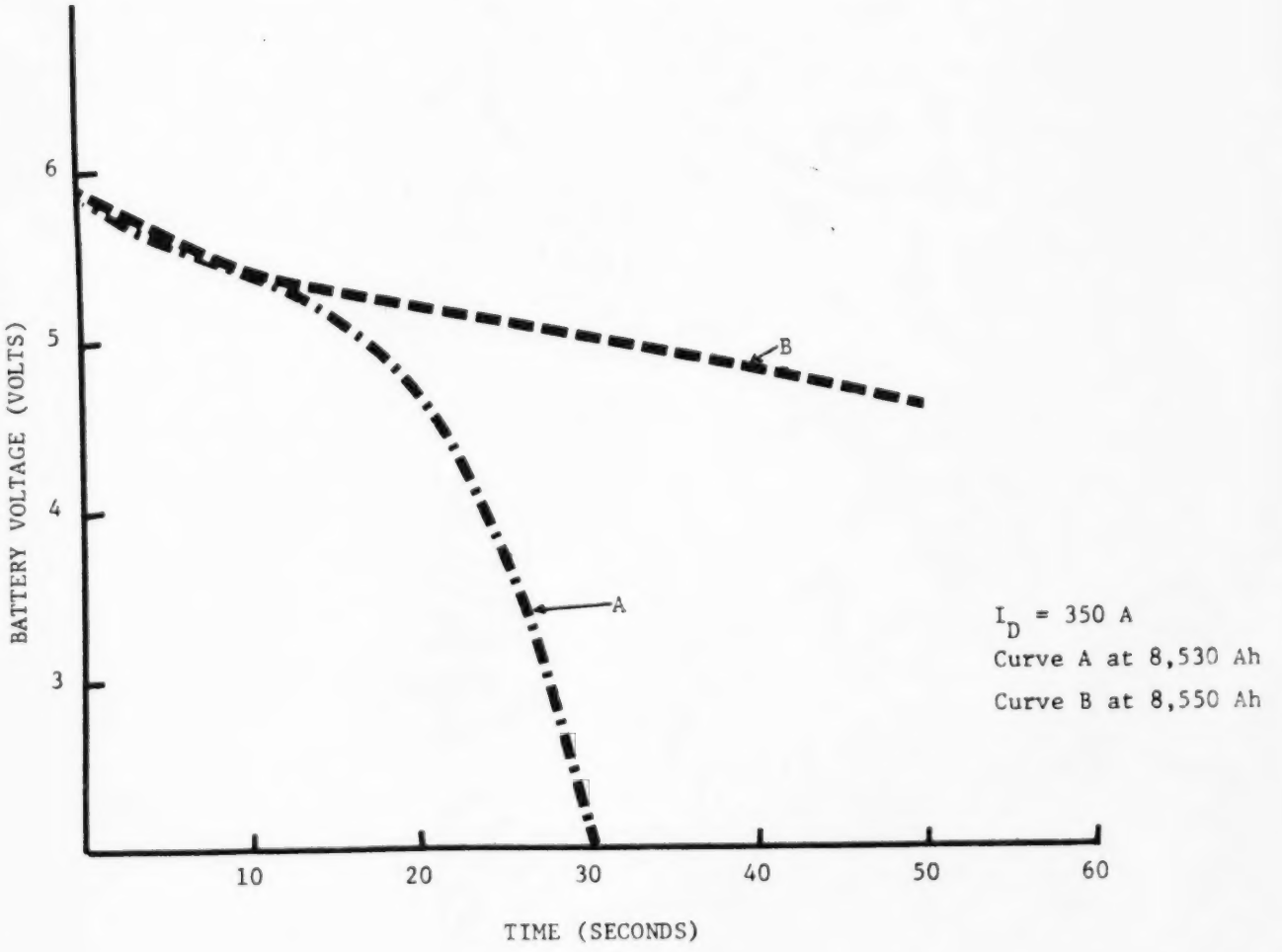

Figure 14. POWER TEST PERFORMANCE FOR ADVANCED, HIGH RATE, EAGLE-PICHER BATTERY #2H

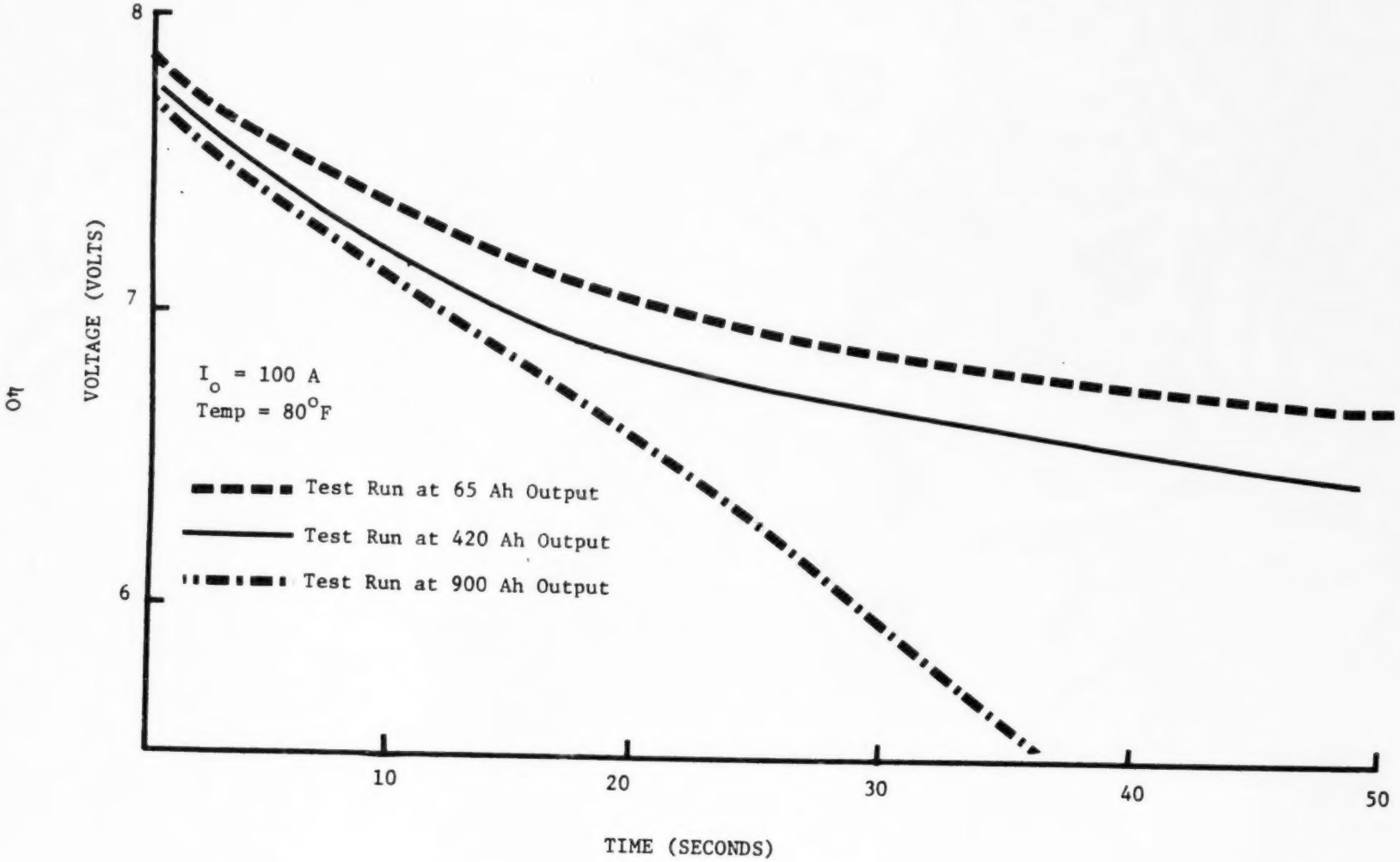

Figure 15. POWER TEST PERFORMANCE OF ENERGY RESEARCH CORPORATION, 5 CELL, 4 Ah, Ni-Zn BATTERY

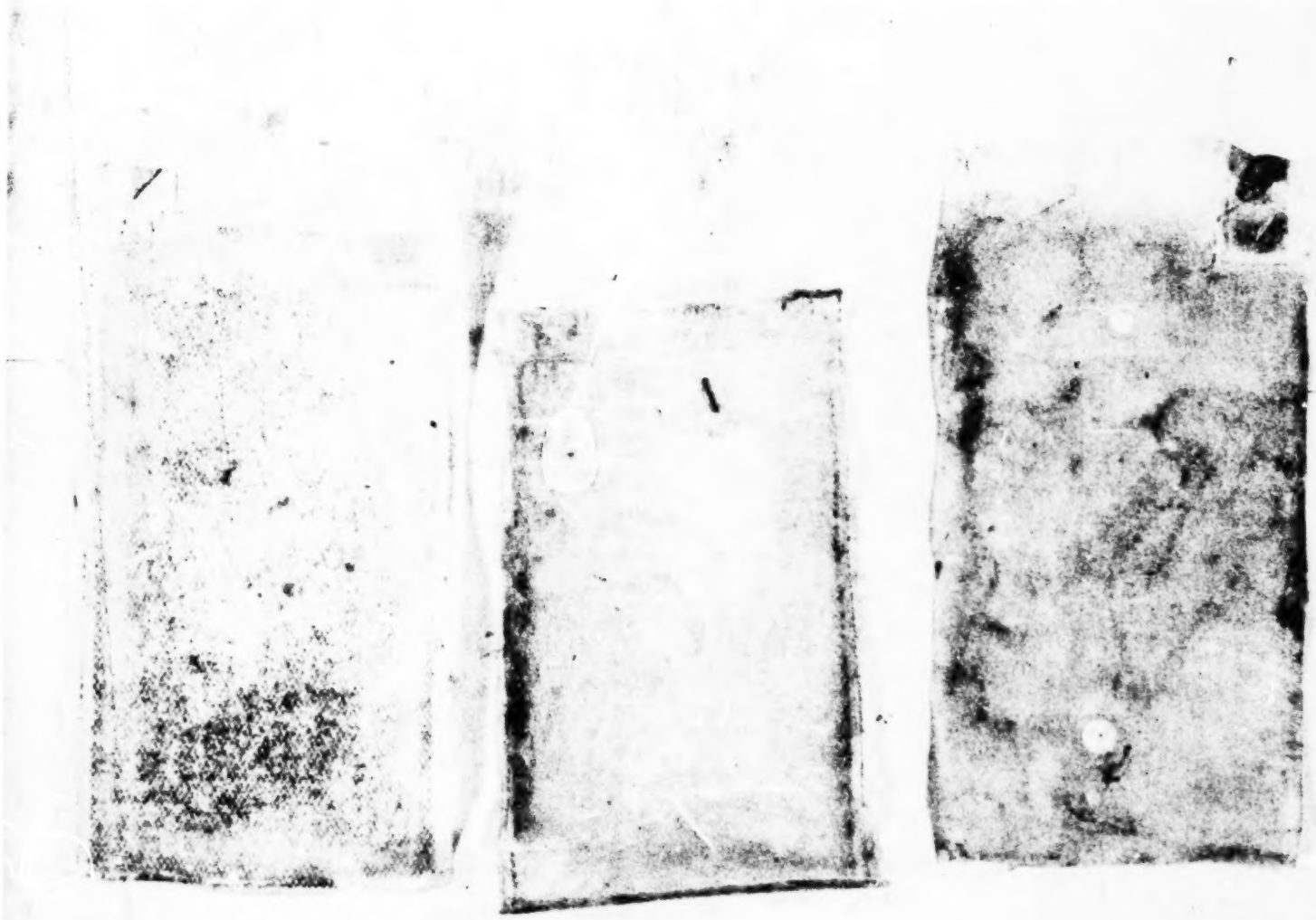

Figure 16. SEPARATOR REMOVED FROM STANDARD EAGLE-PICHER BATTERY #1 AFTER 13,000 Ah

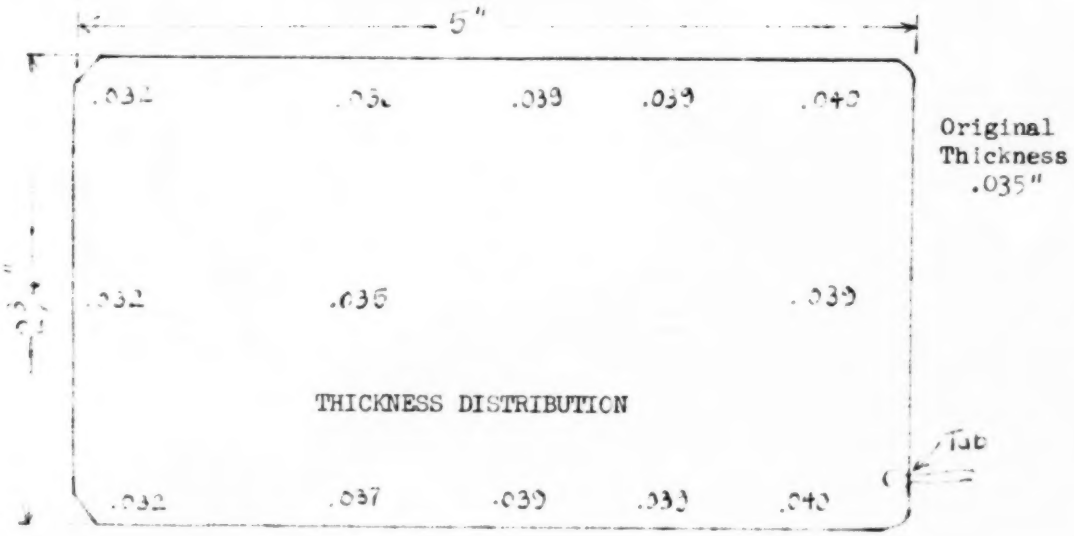

Figure 17. ZINC ELECTRODE REMOVED FROM STANDARD EAGLE-PICHER BATTERY #1 AFTER 13,000 Ah

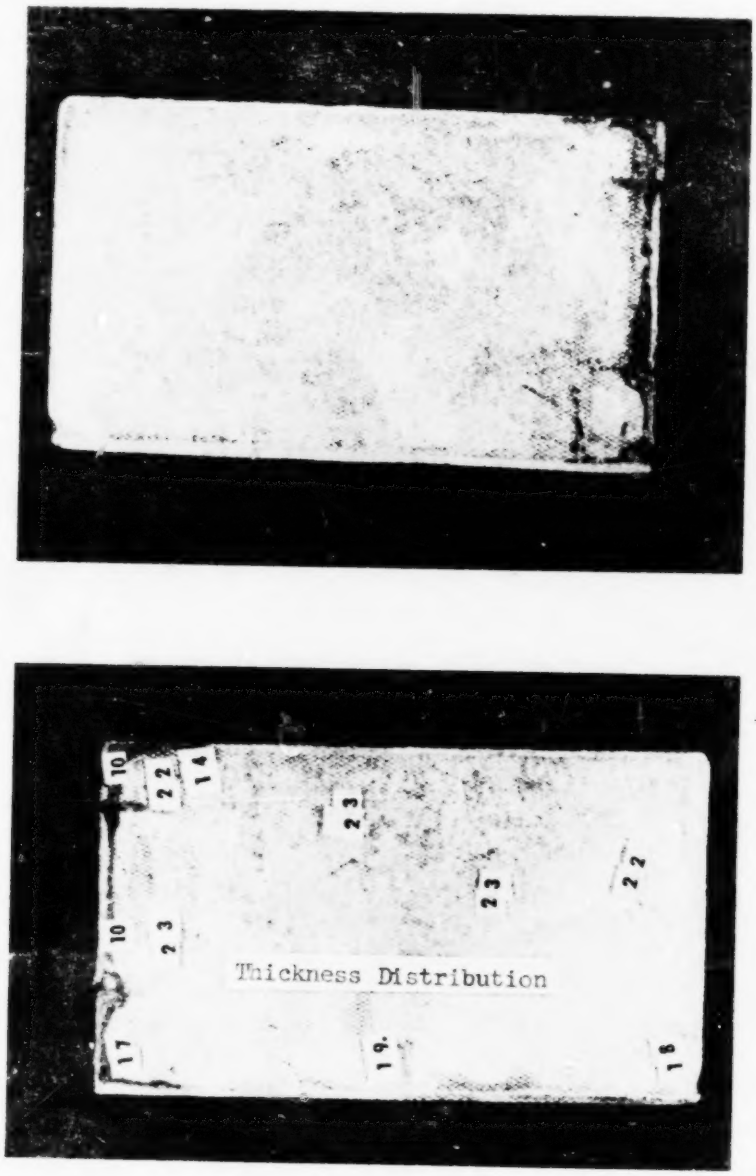

Figure 18. ZINC ELECTRODE REMOVED FROM ADVANCED, HIGH RATE EAGLE-PICHER BATTERY #2H AFTER 26,400 Ah

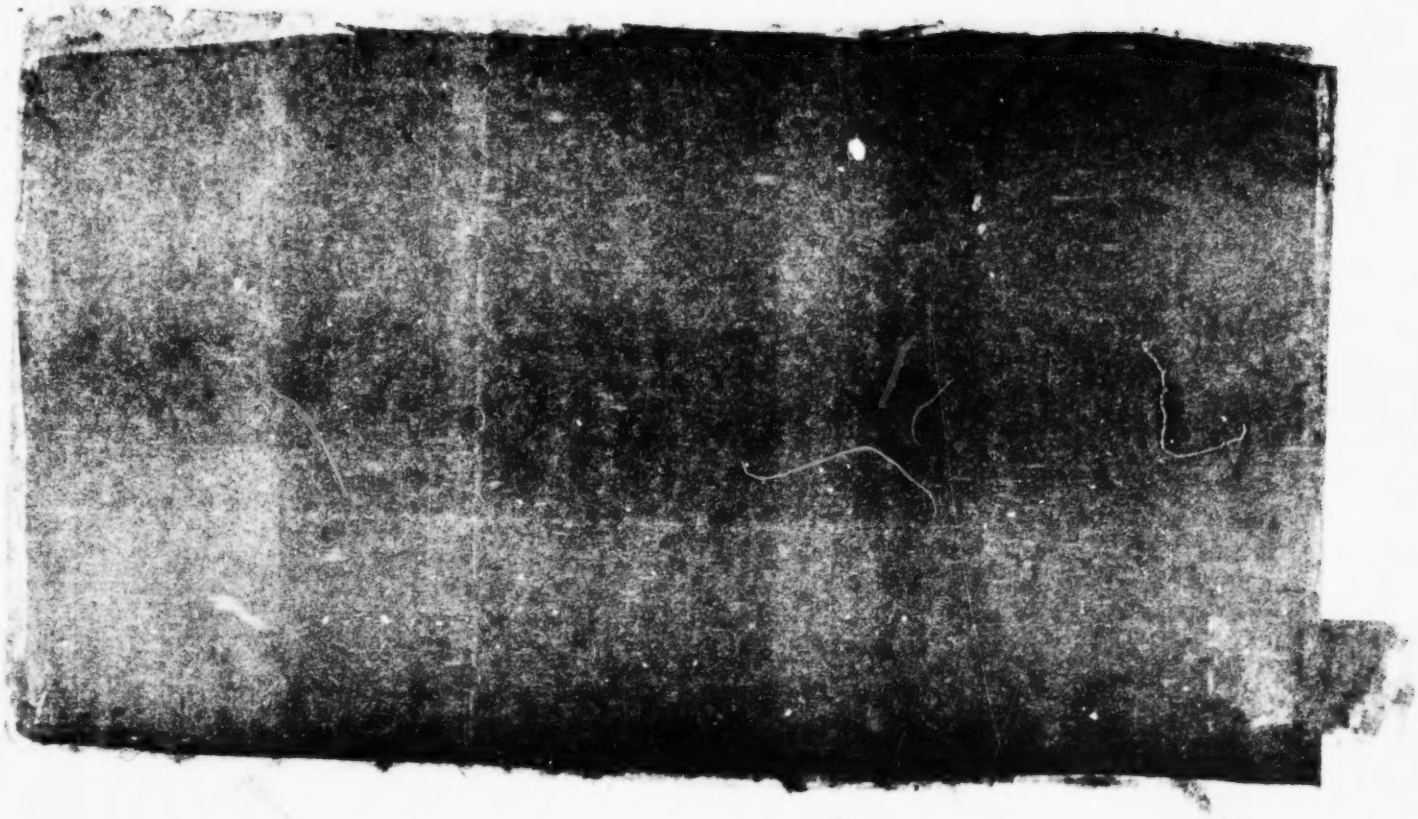

Figure 19. NICKEL ELECTRODE REMOVED FROM STANDARD EAGLE-PICHER BATTERY #1 AFTER 13,000 Ah

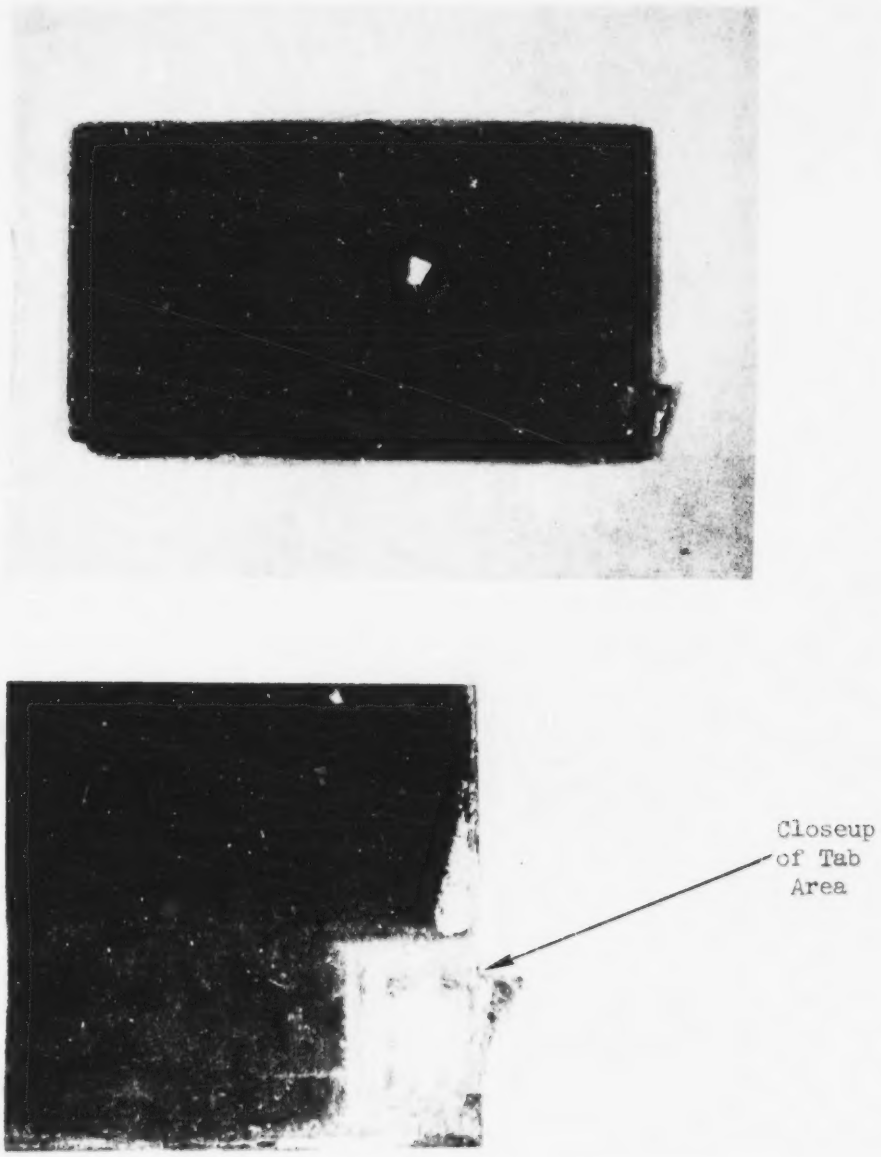

Figure 20. NICKEL ELECTRODE REMOVED FROM ADVANCED, HIGH RATE, EAGLE-PICHER BATTERY #2H AFTER 26,400 Ah

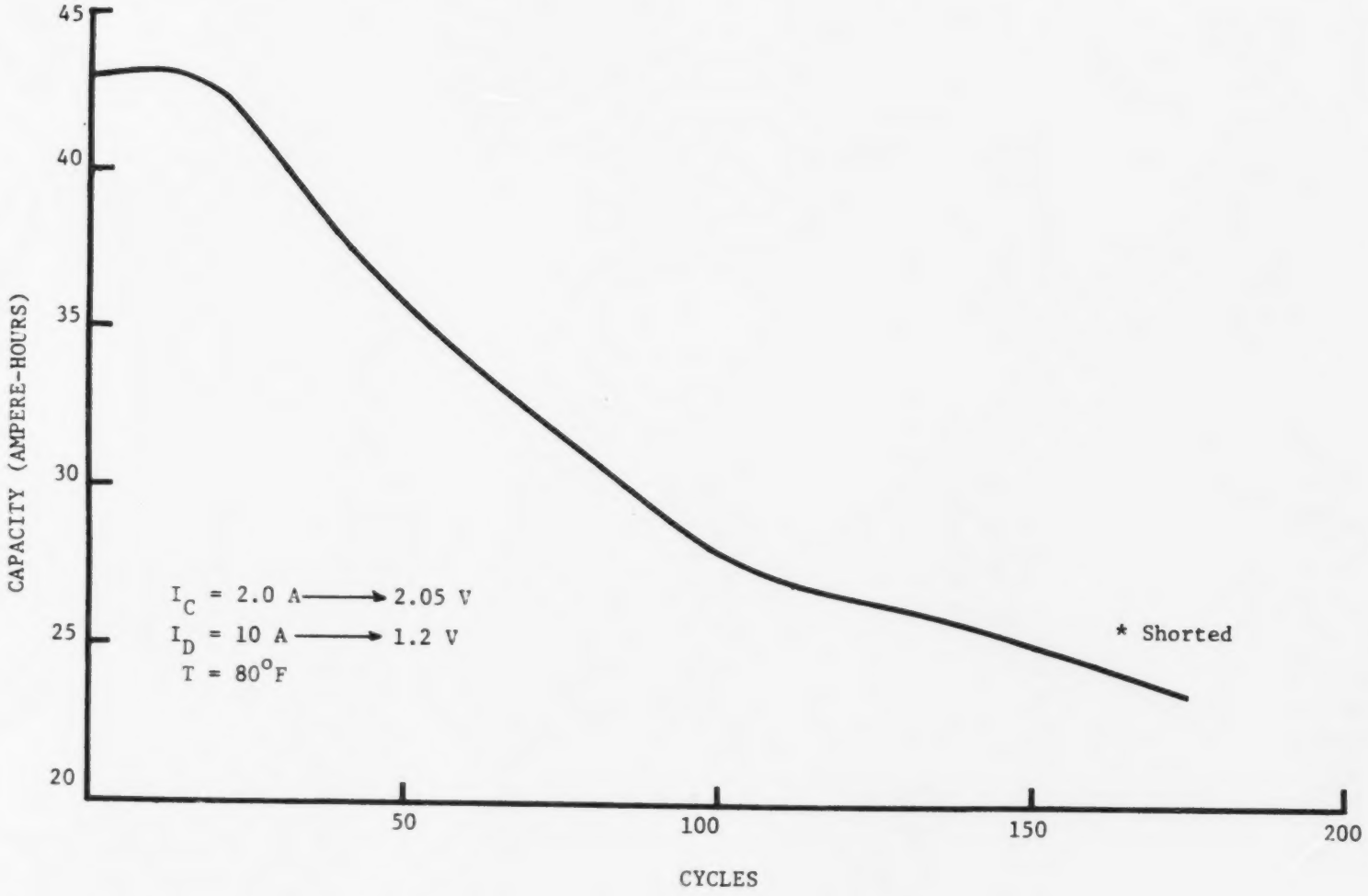

Figure 21. CAPACITY MAINTENANCE OF ASTROPOWER SEALED 40 Ah SILVER ZINC CELLS

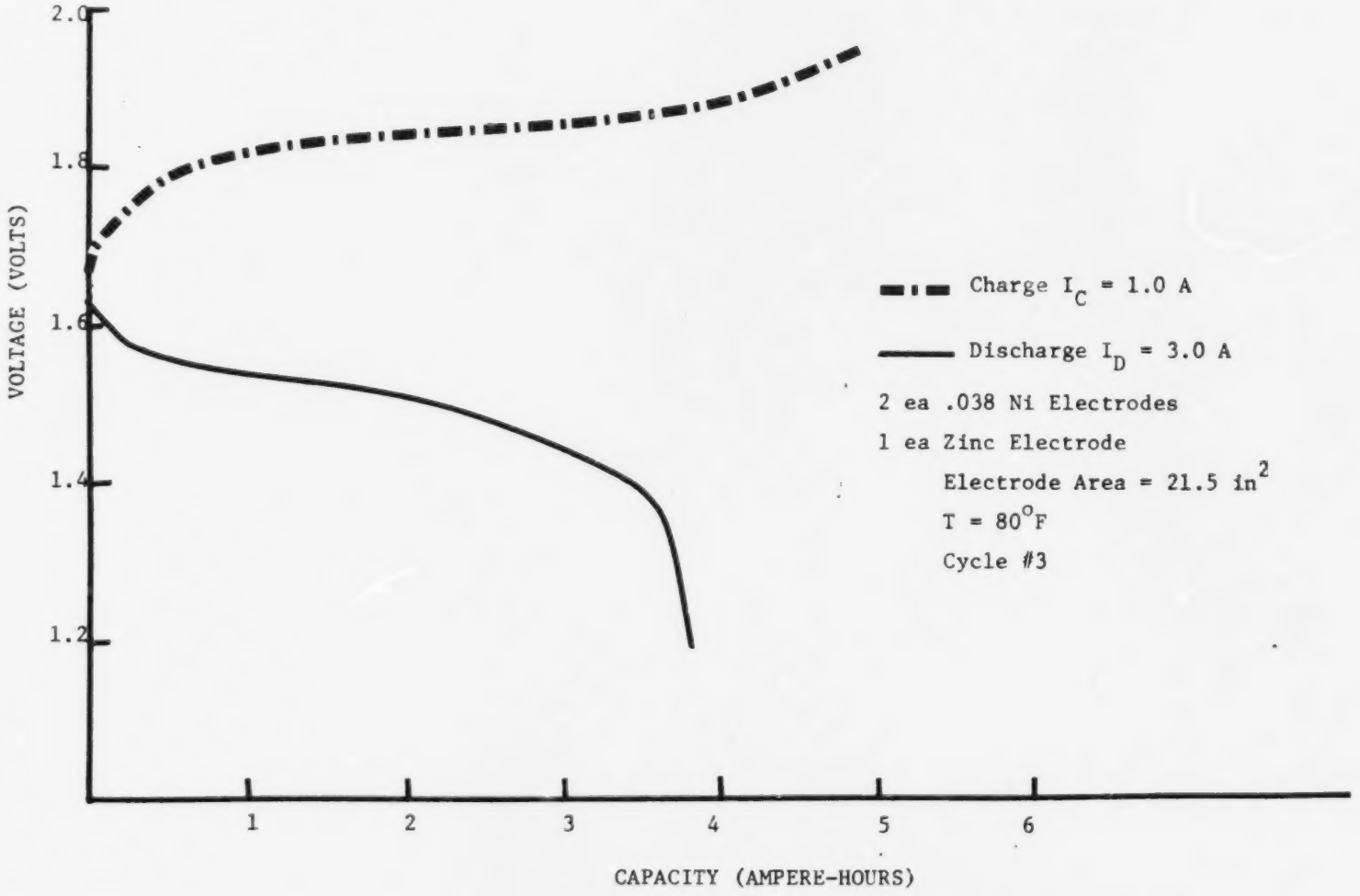

Figure 22. CHARGE-DISCHARGE CHARACTERISTICS OF A Ni-Zn CELL WITH ASTROPOWER SEPARATOR AND ZINC ELECTRODE

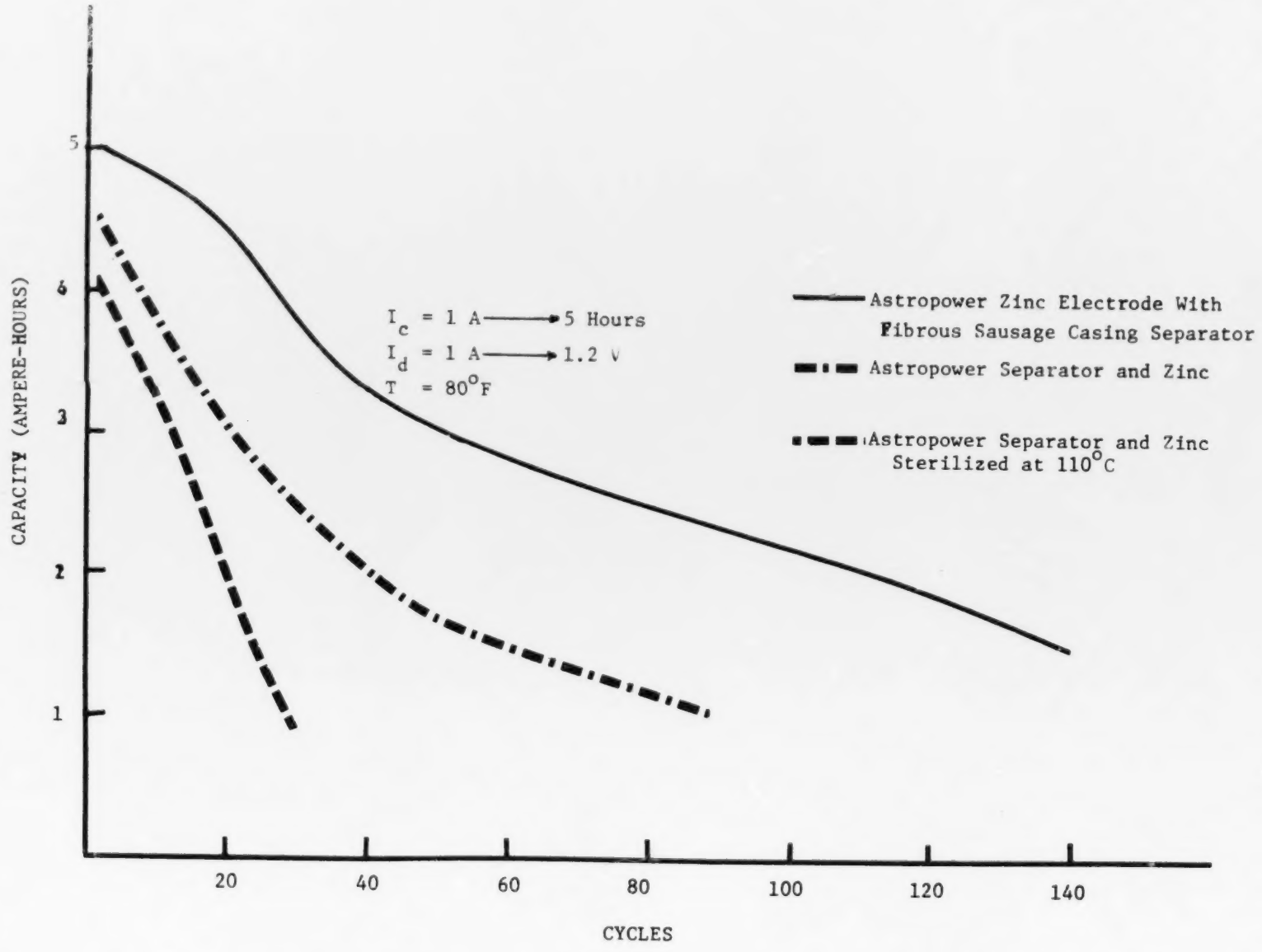

Figure 23. CAPACITY MAINTENANCE OF Ni-Zn CELLS WITH ASTROPOWER SEPARATOR AND ZINC ELECTRODES